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Industrialization of hybrid and additive manufacturing - Implementation to Finnish industry (HYBRAM)

Riipinen, Tuomas; Kujanpää, Veli; Komi, Erin; Kilpeläinen, Pekka; Savolainen, Mikko; Puukko, Pasi; Vihinen, Jorma; Coatanea, Eric; Mokhtarian, Hossein

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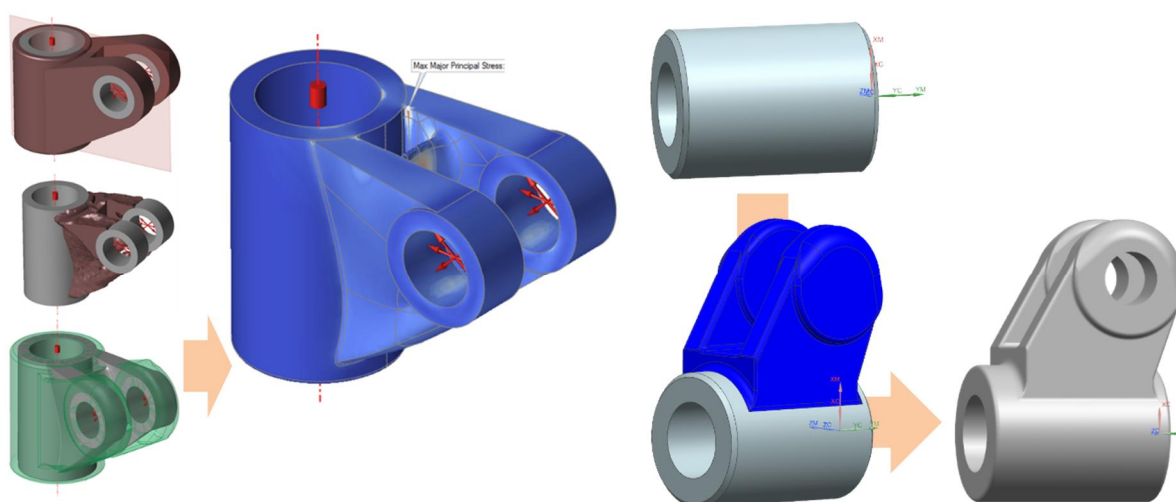


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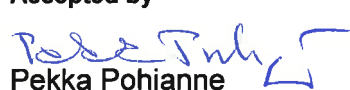
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Industrialization of hybrid and additive manufacturing - Implementation to Finnish industry (HYBRAM)

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Summary <p>This report summarizes the main findings of the public part of the HYBRAM Research Benefit project carried out in 2016-2018, where the aim was to identify the main barriers for implementing Additive Manufacturing technologies in the Finnish manufacturing industry. The features and limitations of laser powder bed fusion, directed energy deposition and hybrid manufacturing technologies are analyzed to provide an overview of the capabilities of modern machines as well as to describe the limitations. The state-of-the-art of automation and integration capabilities of AM production systems are reported. Industrial demonstrator parts were studied to assess the applicability of AM as a production method from the design, technical feasibility, cost and quality point of views. The report also contains a chapter dedicated to explaining the dimensional analysis conceptual modeling (DACM) framework as a modeling approach for AM.</p>	
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Preface

This report describes the research work carried out and the results achieved in the Business Finland (Tekes) Research Benefit project “**Industrialization of hybrid and additive manufacturing - Implementation to Finnish industry (HYBRAM)**” in 2016 - 2018. This was a parallel project of industrial companies, VTT and TUT. Its aim was to industrialize additive and hybram manufacturing in different ways, with the primary goal being to realize new business activities in AM and hybrid technologies. The focus of this project report is on the public part of the parallel project.

The project was supported by and executed in collaboration with five Finnish companies, Sandvik Mining and Construction Oy, Fastems Oy Ab, CM-Tools Oy, PTH-Metalli Oy and Enmac Oy. The project work was supervised by the steering group including a representative from each company, VTT, TUT, Tekes (currently Business Finland) and Technology Industries of Finland:

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Harri Nieminen, Fastems Oy Ab
Juha Martikainen, CM-Tools Oy
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Tuomas Riipinen, VTT Technical Research Centre of Finland Ltd, secretary (1.5. - 31.8.2018)

The authors wish to acknowledge the contribution of all the steering group members during the whole project.

Espoo, November 2018

Authors

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1. Background and project introduction

Additive manufacturing (AM), more commonly known as 3D-printing, has gotten remarkable attention in Finland and globally during the last years. Polymer 3D-printers for home use have increased the interest of consumers, while simultaneously large international companies have invested significant sums of money in metal printers.

The implementation of the technology requires that its effects on the systems and all the processes of the whole factory can be taken into account. These are e.g.

- Product design or re-design taking into account all the possibilities and advantages of additive manufacturing
- Pre-processing steps such as powder handling and design of supporting structures
- Detaching parts from build platform, removal of support structures and post-processing such as heat treatment, machining and grinding
- Control of the system and connection to the factory control
- Quality control of different steps

Additive and hybrid manufacturing affect productivity in many ways in different process steps. It is dependent on product volume (small batch or serial production) and product portfolio.

In the Hybram project the key barriers for implementation of AM in industrial manufacturing environments were studied and this report focuses on describing and discussing the main findings. The features and limitations of laser powder bed fusion, directed energy deposition and hybrid manufacturing technologies are discussed to provide an overview of the challenges related to implementation and automation of these technologies. The state-of-the-art in automation solutions in metal AM and future trends are reported. Industrial demonstrations were also studied with the purpose of analyzing the applicability of different AM technologies. During the project a dimensional analysis conceptual modeling (DACM) framework as a modeling approach for AM was developed further, with the main results reported.

2. Stages and features of additive and hybrid manufacturing

Additive manufacturing technologies are typically considered advantageous for making small batch size production economically more feasible and enabling manufacturing of complex geometries not feasible with traditional manufacturing methods such as casting. The most widely adopted metal AM methods are laser powder bed fusion (L-PBF) and directed energy deposition (DED). Both technologies have gained a stronger foothold in the manufacturing industry as the technologies have matured and knowledge of the processes has increased. Manufacturers that have acquired AM technologies, or are considering to do so, eventually face the question of how to integrate the new technology into an existing production environment. The first step is to identify all the relevant manufacturing steps in the AM process. For L-PBF, DED and hybrid manufacturing the manufacturing steps can be divided into five categories; design, material handling, part manufacturing, post processing and quality control (Figure 1).

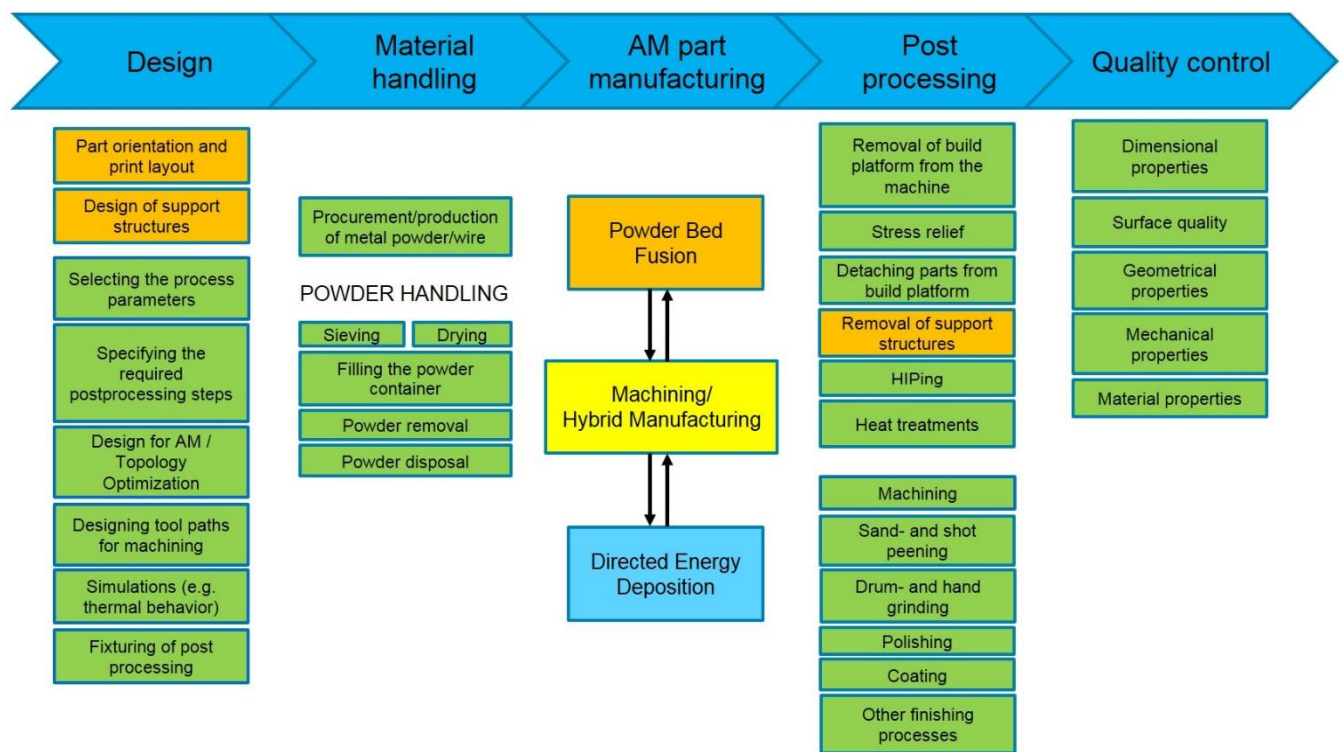


Figure 1. The process phases for additive and hybrid manufacturing technologies.

In the design phase, a 3D model of the component is created and modified if necessary to improve the printability of the component. The correct process parameters are selected and for L-PBF the print layout and support structures are designed. The layout and support structure design depend on the component and the objective, which could be minimizing the volume of support structures for easier removal or better surface quality. The amount of input in the design phase depends on the complexity of the task, but even simple parts require some skill and knowhow on 3D printing. The process parameter selection is straightforward if parameters are obtained from the powder supplier for a specific machine. Otherwise, it can be relatively laborious to determine the suitable process parameters as it requires

experimental tests. The design phase is mostly done manually although certain tasks can be automated to some degree.

All of the material-related preparation work is done in the material handling phase. The feed material can be in either powder or wire form for DED, and only as powder for L-PBF. The material can be purchased from the machine supplier or directly from the material manufacturer. Nowadays many suppliers offer powders tailored specifically for AM, meaning that the end user does not have to modify the powder prior to use. However, the powders should be dried prior to printing to avoid the negative effects of oxidation. Modern industrial scale L-PBF printers have integrated powder handling units, which circulates the powder in the machine, increasing the level of automation. Powder disposal is typically done manually, but some models have a modular design that enables automated powder disposal.

The manufacturing phase is largely automated, but requires manual preparation work before and after the printing process, such as preparation of the build platform, print file and powder feed. Manual input is also required by the operator in the event of unexpected sensor malfunctions and other errors that halt the printing process. A major challenge in the build process phase is quality monitoring for detecting defects and machine related problems during the build process. Different quality monitoring systems are available for some DED and L-PBF systems, but at the moment the monitoring is passive, meaning that the defects can be detected during the process but the process parameters can not be adjusted dynamically.

Almost all 3D printed parts are post-processed in some manner, most typically heat-treated to improve mechanical properties and machined to the desired tolerances. The post-processing steps are taken into account already in the design phase by adding the required machining tolerances to the CAD model and planning the support removal, surface treatments and heat-treatments in advance. L-PBF manufactured parts are typically stress relief heat treated while the parts are still attached to the build platform to prevent warping and cracking. The removal of the build platform is done manually except for the largest L-PBF machines, however some machine manufacturers have started to implement zeropoint clamping for the build platforms where the build platforms can be attached and detached automatically by a robot arm.

The features, advantages and challenges of DED, PBF and Hybrid processes are described in more detail in the subsequent chapters.

2.1 Directed Energy Deposition (DED)

Directed energy deposition (DED) is an additive manufacturing process where focused heat energy is used to melt material deposited from the nozzle. The heat energy melts a small amount of base material along with the deposited material. The techniques used in DED have long been known in cladding. Cladding consists of applying a uniform buildup of material on a surface. In DED process the build features are constructed layer-by-layer. Material is added only in required places.

As a source of energy, laser, electron beam, plasma arc or cold spray can be used (Figure 2). Laser is by far the most widely used source of energy and therefore the following sections will concentrate to laser processes. Approximately 90% of the DED devices use laser as an energy source and powder as materials.

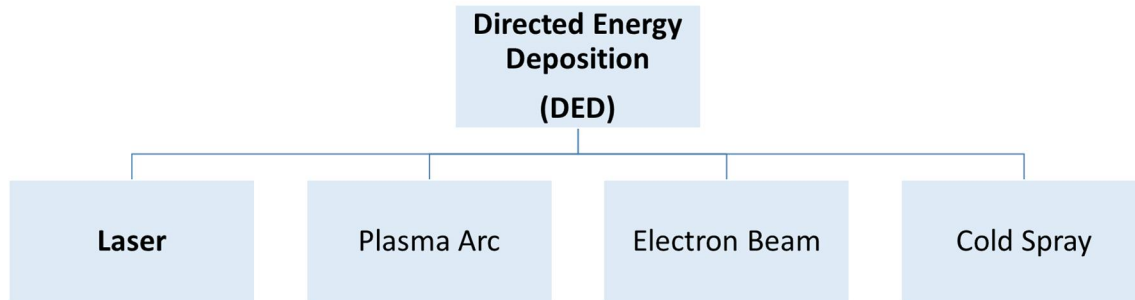


Figure 2. Energy sources for Directed Energy Deposition processes.

DED systems have ability to produce relatively large build volume due to the high laser power and does not necessarily require enclosed chambers. Most commercial equipment, however, have a closed chamber that helps to ensure the homogeneity of the process in inert gas environment. DED technology enables the creation of shapes and features over existing 3D surfaces more easily than PBF technology because the deposited material is delivered directly to the melt pool.

The deposited material is usually imported as a powder or a wire, although narrow strips are sometimes used. The diversity of the sources of energy and deposited materials makes it possible to do many things with a DED process, but at the same time makes comparison and choice more challenging. At low power the laser beam diameter can be a few tens of micrometers and at high power up to 20 mm. Generally, the laser power varies between 400-4000 W. Even higher powers are used, but then the details of the features are rougher due to the large melt pool. The powder is usually fed to the nozzle 1 to 50 g/min. The typical powder capture efficiency is 40-80%. In some cases, up to 95% efficiency can be achieved. Powders used in spraying processes (e.g., size 45 to 150 μm) may be used also in DED processes, whereby the price of powder is more advantageous than powders used in L-PBF processes. Typically materials used in DED processes are same as in L-PBF processes; stainless steels, tool steels, titanium alloys, aluminium alloys. The use of powders makes it possible to change the material. Some manufacturers have several powder feeders from which the material can be quickly replaced. It is also possible to make a gradient structure.



Figure 3. Multi-material disc, base material P21 and small details of aluminum bronze (Insstek).



Figure 4. Big mold half (diameter about 500 mm). Two AM techniques have been used in the production of the piece. An inexpensive frame is built with a layer lamination. In this case, the laser-cut sheets with the cooling channels are joined together, and the final mold material is added to the coarse form by a DED (laser + powder). (Trumpf).

Using plasma arc, electron beam and cold spraying in AM manufacturing is less common, but they are very promising methods in the cases where high deposition rate is required. Below are some examples of parts made with these methods (Figure 5, Figure 6, Figure 7).



Figure 5. A piece manufactured with an arc welding device. Material EN 1.4316, weighing 25 kg, deposition rate 325 cm³/h. Machining 28% (7 kg). Total cost for 2000 € (Gefertec).



Figure 6. Features added by electron beam (Skiaky). The method can apply material up to 9 kg/h.

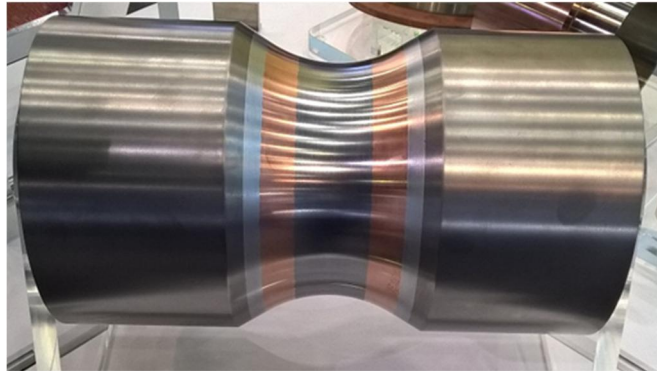


Figure 7. A test piece showing the possibilities of a cold spraying. Sprayed material 25 kg, manufacturing time 3 h 45 min. Materials AISI 316L (density > 96%, deposition rate 9 kg/h), copper (density > 99%, deposition rate 10 kg/h), aluminum (density > 90%, deposition rate 3.5 kg/h) and titanium (density > 97%, deposition rate 6 kg/h). Impact Innovations.

2.2 Laser Powder Bed Fusion (L-PBF)

2.2.1 Developments and current status

Laser powder bed fusion (L-PBF) is the most utilized metal additive technology in the world at the moment. The machines have developed steadily over the years and have become more reliable and efficient. In recent years the machine manufacturers have focused on developing the industrial scale production capability of the technology. The production rate and efficiency of the machines keeps increasing with the implementation of improved optics, larger build chambers, automated powder handling systems and quality monitoring systems. In addition to the hardware improvements, the software capabilities keep developing at a very fast pace. Several companies offer simulation features that calculate the residual stresses and displacement of parts during the printing process. Metal material groups available for L-PBF include tool steels, stainless steels, titanium alloys, commercially pure titanium, aluminium alloys and commercially pure aluminium, nickel-based alloys and pure nickel, copper based alloys, cobalt-chromium alloys, precious metals and also hard metals and superalloys. The list of available materials grows continuously as a result of active material research. Many material suppliers offer gas atomized powder tailored specifically for L-PBF. The material portfolio is limited due to challenges in processing materials that are prone to cracking and other defects.

L-PBF machines typically utilize one to four Nd:YAG fiber lasers each with maximum powder output of 200-1000W. The build platforms vary in size from less than 100mm² to over 400mm². The build chamber is purged with inert gas (typically Argon) before operation and the gas atmosphere is maintained during the process to keep the oxygen level very low. The build rates depend on the number of lasers and ranges from 15 cm³/h to over 100 cm³/h for an industrial scale machine. The major machine manufacturers have developed quality monitoring systems for their machines that are explained in more detail in section 2.2.3. Some properties of L-PBF machines are shown in Table 1. As with any other manufacturing process, there are many sources of defects within the laser melting process. Some of these possible defects include thermal distortions, cracking during printing or heat-treatment, porosity, lack of interdiffusion, micro cracks, edge effect, restart marks, dross formation and transversal shrinkage. These issues can, however, be minimized or avoided completely by using optimal process parameters, support design and part orientation.

2.2.2 Quality in L-PBF

Quality is a measurable property related to dimensional tolerances, mechanical properties, surface roughness and other relevant quality metrics. A part must satisfy the company or international standards in the same manner as with other manufacturing technologies. If the quality metrics that are defined in the standards fit within the acceptable range, the quality can be considered sufficient. The quality of a manufacturing process can be improved by reducing the variability in the measurable quality metrics. In L-PBF the quality of the printed part is affected by the process parameters, powder properties, building process and post processing steps. The process parameters include laser parameters, energy input and scanning strategy. The building process related properties include the consistency of the recoated powder layer, build chamber atmosphere, gas flow properties and platform heating. Powder properties comprise of chemical composition, particle size distribution, morphology, flowability, optical and thermal properties. The post-processing steps typically related with printed parts are heat-treatment, part removal, machining and surface treatments. Commonly used approaches and the related challenges are presented in Figure 8.

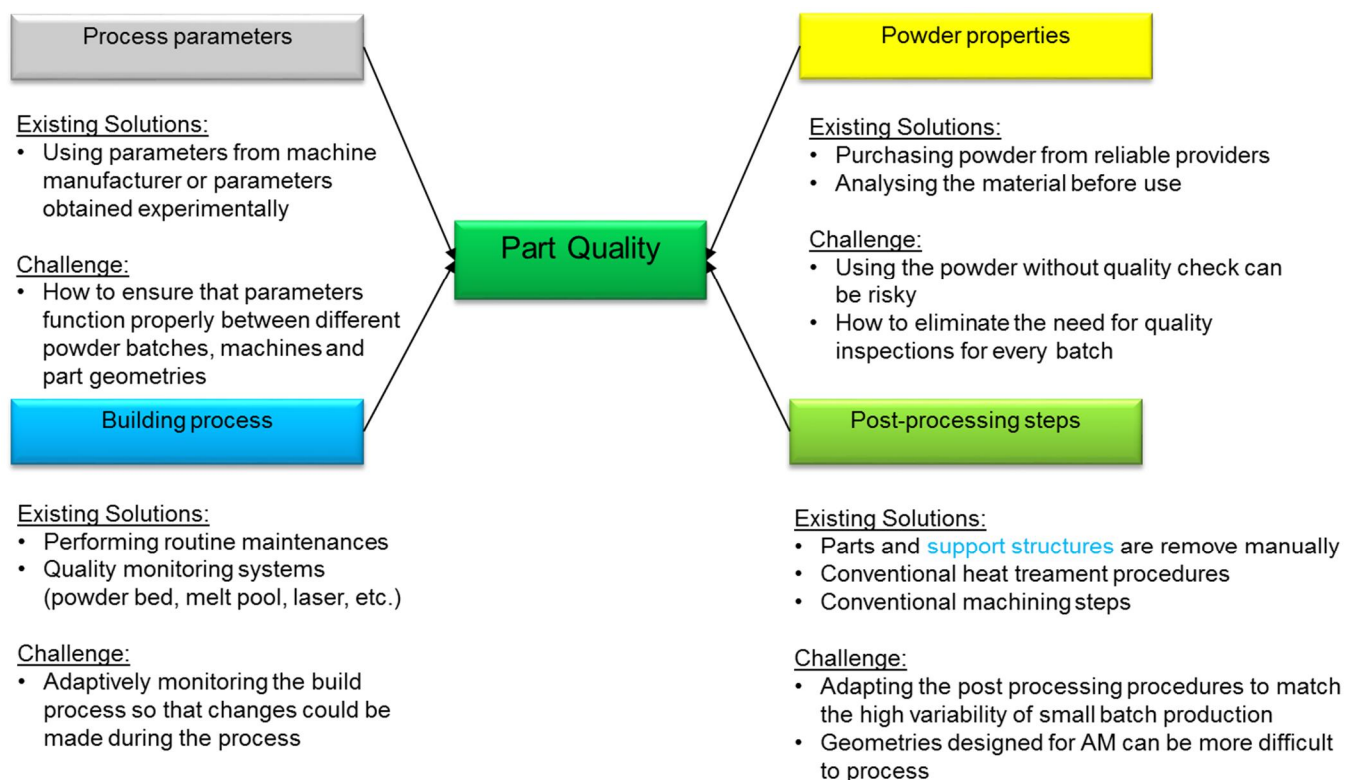


Figure 8. Quality related solutions and challenges in L-PBF.

The main challenges related to the process parameters derive from the fact that the same parameter profile is not necessarily optimal for all part geometries and sizes, powder batches and machine configurations. Changes in these properties may lead to increased porosity, surface roughness and thermal distortion. However, for most cases the standard parameters work sufficiently.

The powders are typically purchased from the machine manufacturer, AM powder supplier or directly from the powder manufacturer. AM tailored powders are modified to work well in

powder bed machines with a quality guarantee. Not all powders are what is promised and ultimately the end user has the responsibility to analyze the material batches to ensure sufficient quality.

All the systems that control the build process influence the quality, such as laser optics, powder recoating, build chamber atmosphere and gas flow. Machines should be maintained regularly to ensure proper function. Quality monitoring systems should be implemented to provide real-time quality monitoring capability. The quality monitoring systems are discussed in more detail in the following section.

Parts produced with powder bed fusion require a varying amount of post-processing steps after the build process, but some of them are common to all parts, such as removal of parts from the build platform and cleaning the excess metal powder from the part and platform. It is very common that heat treatment cycles are done prior to removal of the parts to release stresses and to improve the mechanical properties. Most parts are also machined at least partially to achieve the required dimensional tolerances and surface quality. These steps are heavily reliant on manual labour and conventional process knowledge. Challenges arise from the high variability in L-PBF production where the part sizes, shapes, support designs and heat treatment requirements can vary greatly. Complex support structures can be difficult to remove and conventional heat-treatments do not always apply to L-PBF printed parts that require heat treatment cycles specifically designed for L-PBF parts.

AM technologies and especially L-PBF is capable of producing high quality parts that satisfy the requirements of demanding applications such as within the aerospace industry. However, unified quality assurance practices and better standardization is required to make the technology more accessible where robust quality assurance methodologies are in place. Work is being done in standardization and technology development to make improvements in these matters.

2.2.3 Quality monitoring systems

Ensuring reproducibility of part quality in industrial production is a major challenge in AM, especially in highly regulated industries such as medical device manufacturing and aerospace. Quality assurance methods aim to reduce the variability and uncertainty of the process variables to provide confidence for high quality production. Powder bed fusion technology enables real-time process monitoring due to the the layer-by-layer nature of the process. Process monitoring systems are used to measure the process signatures with either local or global sensors. The most typical signatures emanating from the laser-powder interaction are shown in Figure 9. The local sensors measure local phenomena such as melt pool properties and laser-powder interaction. The local sensors are used to capture the electromagnetic signal of the melt pool using photodiodes, pyrometers, cameras and spectrometers. In order to effectively monitor the melt pool properties the sensors require a fast response time and high spatial resolution. Sensors such as photodiodes and pyrometers are commonly utilized in current commercial monitoring systems and they capture data at very high rates (≥ 50 kHz). The type of the sensor defines the range of wavelengths that can be measured. CCD or CMOS detectors are used to evaluate the melt pool size by counting the number of pixels over certain threshold values. Spectrometers have not been adopted widely in the L-PBF process due to low response times relative to the movement of the laser. A commonly utilized optical arrangement for quality monitoring in L-PBF is shown in Figure 9, where the reflected beam can be measured using a beam splitter, allowing the sensors to follow the melt pool. Most of the major PBF machine providers offer some process monitoring capabilities in their systems.

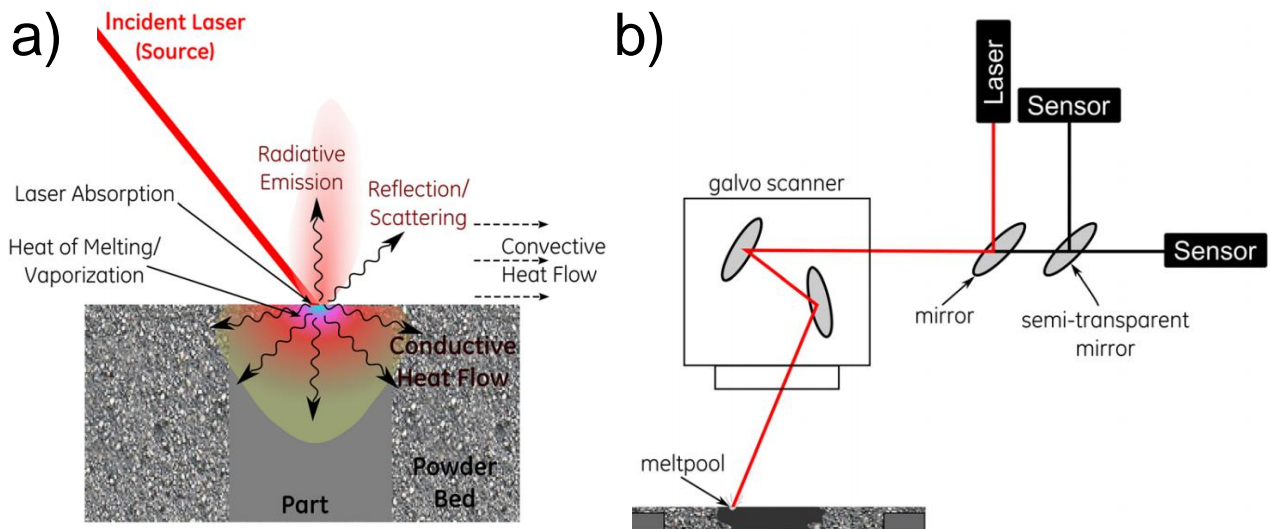


Figure 9. a) Process signatures of the meltpool and b) optical arrangement of a melt pool monitoring system. (Spears & Gold, 2016)

The global sensors acquire measurement data at much lower rates compared to the local sensors and are used to monitor the entire powder bed or a region of interest. These sensors include cameras for monitoring the powder bed uniformity and machine vision imaging technology, laser profilometry, structured light topography and thermal (infrared) imaging (Wohlers, Campbell, Diegel, & Kowen, 2018). The biggest challenge associated with process monitoring would be to develop a real-time closed-loop feedback control system that reacts to deviations in quality measured in real-time and adjusts the process accordingly. This however would require many improvements, including more advanced predictive models and control algorithms as well as more understanding of the underlying physics (Spears & Gold, 2016).

2.3 Hybrid manufacturing

Hybrid manufacturing is defined in this report as a manufacturing method that combines additive and subtractive processes in one machine for the production of metal parts. Commercial hybrid machines that combine additive manufacturing and milling have been introduced relatively recently. Parts manufactured using only additive methods usually have to be machined afterwards to attain the dimensional tolerances. The integration of machining and AM into the same machine enables adding and removing material in a repeated manner which makes machining of more complex shapes possible. Additive manufacturing methods most commonly utilized in hybrid manufacturing include laser powder bed fusion and directed energy deposition. The different types of hybrid manufacturing systems include the following:

- Directed energy deposition combined with 5-axis milling/Turn mill
- Powder bed fusion combined with 3-axis milling
- Cold metal spray combined with 5-axis milling

2.3.1 Directed energy deposition combined with 5-axis milling / Turn mill

In DED hybrid machines the material is typically deposited from a nozzle in powder or wire form and melted onto the part surface using a laser or other high-energy source (Figure 10). The nozzle can be attached onto a multiaxis arm providing more freedom for material deposition and the part is attached to a lathe spindle or a rotating platform. The various approaches of DED hybrid manufacturing are presented in Figure 11. The DED hybrid machines are basically CNC machines with integrated laser welding deposition capability but

there are also separate deposition heads available that should be applicable to almost any CNC machine.

The flexibility of the hybrid DED manufacturing machines makes them a potential method for part repair, as new features can be added and machined in one go. In some cases it is more cost efficient to repair a damaged part than to manufacture it from scratch. The build rate of DED is relatively high, as is the geometrical flexibility. Multiple materials can be deposited during the DED manufacturing process, which is currently not possible with L-PBF. The dimensional accuracy of parts produced using hybrid manufacturing is as good as with typical CNC milling with the exception that the use of cutting fluids in hybrid machines is limited as they would require additional cleaning steps. The relatively wide melt pool in DED prevents creation of complex support structures and supports in DED are to be avoided if possible to avoid additional processing steps. It can be advantageous to use a Hybrid machine over combining standard DED and CNC machines if the part can be manufactured using a single fixturing, which decreases the number of work steps and the total manufacturing time. However if heat treatments are required the manufacturing should be planned accordingly. This means that the final machining has to be done after heat treatments if dimensional changes can be expected during the heat treatment phase.

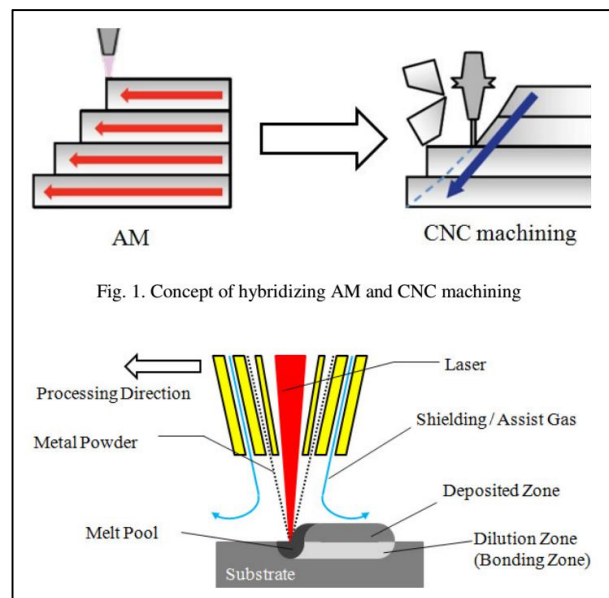


Fig. 1. Concept of hybridizing AM and CNC machining

Figure 10. Schematic presentation of the material deposition and milling steps in Hybrid manufacturing with DED. (Homar & Pušavec, 2017)

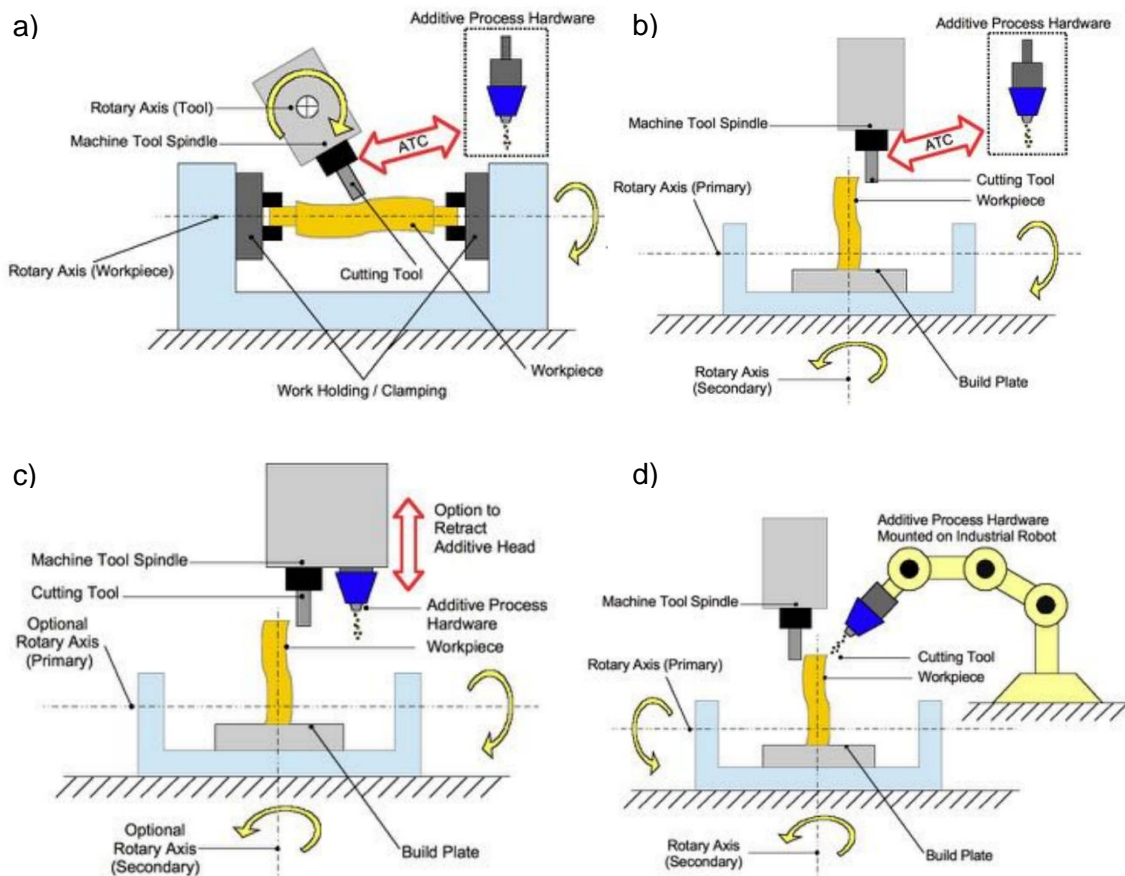


Figure 11. The functioning principles of, a) DED-turn mill with **automatic tool changer** (ATC), b) 3/5-axis with ATC, c) 3/5-axis with permanent mounting and d) 3/5-axis with industrial robot. (Chaharsooghi, 2016)

2.3.2 Powder bed fusion combined with 3-axis milling

The powder bed fusion hybrid machines function as a typical powder bed fusion machine with integrated 3-axis milling capability. The milling step (semi-finishing) is typically done after ten layers have been deposited by laser melting. The step machining process is explained in more detail in Figure 12. The finishing machining is done for the first layers after another ten layers have been deposited to ensure that thermal contraction won't affect the quality. The deposition, semi- and final-finishing steps are repeated for the required surfaces until the part is complete. Due to the relatively good surface finish of as-deposited layers, very little material needs to be machined from the surface. This is beneficial as cutting fluids cannot be used in the build chamber. The material selection for the hybrid process is the same as for typical powder bed fusion. Both conventional and hybrid L-PBF result in similar material density and mechanical properties when the process parameters are chosen correctly. The same basic design rules apply for hybrid manufacturing as for regular L-PBF in terms of using support structures for supporting angled features and improving the heat flow away from the part.

Limitations

The following limitations apply for the machining step: 1) profiles that are in a 90° angle cannot be machined and a slope with a minimum angle of 25° must be added if machining of

the bottom surface is desired, 2) the top surface of internal channels cannot be machined and the channel profile should be a e.g. a waterdrop shape where the top surfaces have an angle $\geq 25^\circ$ to prevent dross formation, 3) the minimum width of an internal channel has to be 3mm or more for it to be machinable. By repeating the laser melting and milling steps the internal features can be machined which is not possible with typical L-PBF process. It also makes the milling of surfaces easier compared to doing it separately. The step-by-step machining however increases the processing time resulting in long build times. The milling is restricted to 3-axis which restricts the machining capability to some degree. The workpiece temperature can rise higher compared to traditional cutting due to the absence of cutting fluids which can increase tool wear. Almost all parts manufactured using powder bed fusion require post heat treatments to relieve stresses and to improve mechanical properties. This can be troublesome in the hybrid process for certain materials as the shape of the part might change during heat treatment. The effect of heat treatment on dimensional accuracy has to be considered early in the manufacturing process. This technology has been promoted most for the mould making industry, which is logical as complex moulds can be manufactured in one step with this process.

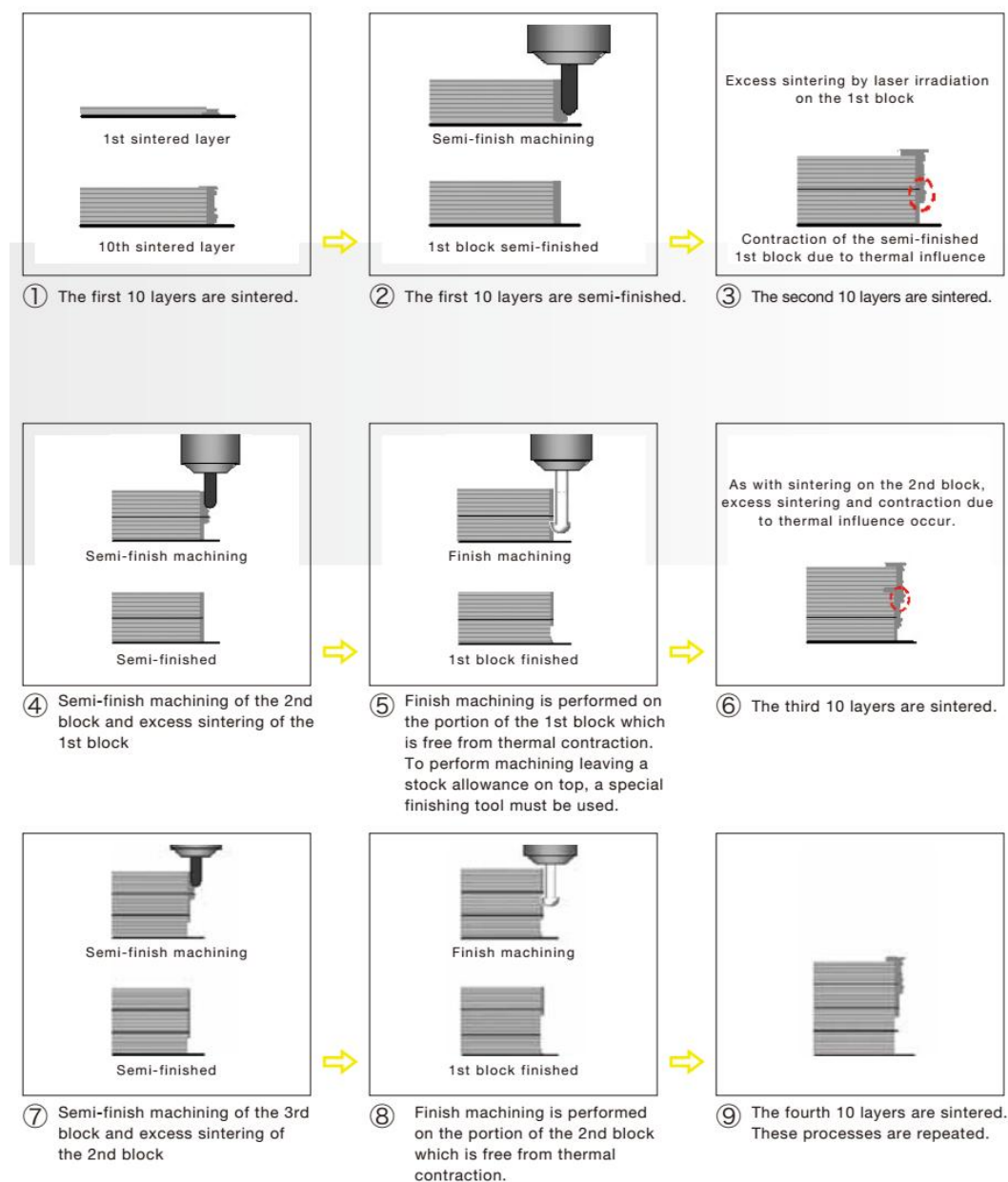


Figure 12. The step machining process for the Matsuura LUMEX series. (Matsuura, 2016)

Applications

The main advantages for L-PBF-hybrid manufacturing are found in applications that have large surface areas that require milling and benefit from the capabilities offered by the layer-by-layer process such as integrated cooling channels. For these reasons injection mold components are often considered potential for this type of process as the part can be manufactured in one go and the internal cooling channels provide improved production efficiency. Two example parts exhibited at Formnext 2017 are shown in Figure 13.

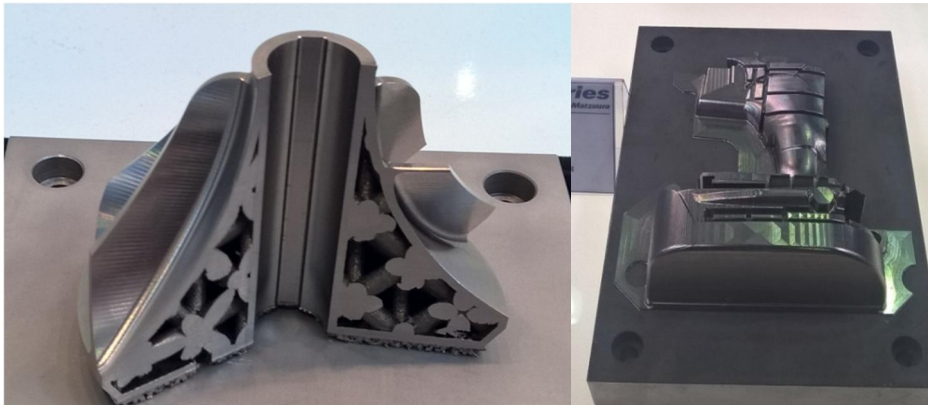


Figure 13. Parts manufactured with L-PBF-hybrid technology. The sectioned component (left) showing the internal lightweight structure and a mold insert with internal channels (right).

2.3.3 Cold metal spray combined with 5-axis milling

The third hybrid manufacturing technology is cold spray combined with 3-axis milling capability. In cold spray the powder particles are heated to a temperature below the melting temperature and accelerated to supersonic speed by a high-velocity gas jet. Upon impact with the substrate the particles undergo plastic deformation and adhere to the surface. The metallic bonding mechanisms are mechanical interlocking and metallurgical bonding (Figure 14). Cold spray is traditionally used as a coating technology but it can also be used in to add material in layer by layer manner, making hybrid manufacturing with cold spray possible. Due to the low process temperature of the cold spray the thermal input to the substrate is low and the deposited material does not melt or undergo phase change and grain growth. Layers deposited using cold spraying generally have very high density. Dissimilar materials can be deposited using cold spray as the low thermal input prevents the formation of unwanted phases that could induce cracking. The high deposition rate of the process can also be considered a benefit. On the other hand the process requires a high level of process control (deposition velocity, temperature, particle size, morphology) and results in low ductility in the deposited material due to the plastic deformation. The range of sprayable materials includes pure metals (Al, Cu, Ni, Ti, Ag, Zn, Ni) and metal alloys as well as metal-ceramic mixtures that have a sufficient degree of low-temperature ductility. The particle sizes of the cold spray powders are generally lower compared to L-PBF and DED processes as particle sizes below 25µm are common.

The German machining centre manufacturer Hermle has been developing a cold spray additive technology it calls Metal Powder Application (MPA), that promises build rates that can exceed 200 cm³/h. Two different materials can be applied during the process and the milling step is repeated when necessary. Internal channels are added by filling channels with water soluble material which can be dissolved after the part is finished. Materials currently available for the MPA technology include hot working steels, cold-working steels, stainless steels, invar and pure metals such as iron, copper and bronze. Some example parts produced with the MPA technology with internal channels and embedded wiring are shown in Figure 15.

Limitations

Cold spray has is a widely used technology for adding coatings to material surfaces. The utilization of cold spray for additive manufacturing is however in very early stages at the moment as there are no Cold spray/milling hybrid systems commercially available. Despite the benefits of low thermal input described earlier the low ductility of deposited material layers limits the material portfolio and can cause difficulties during post processing.

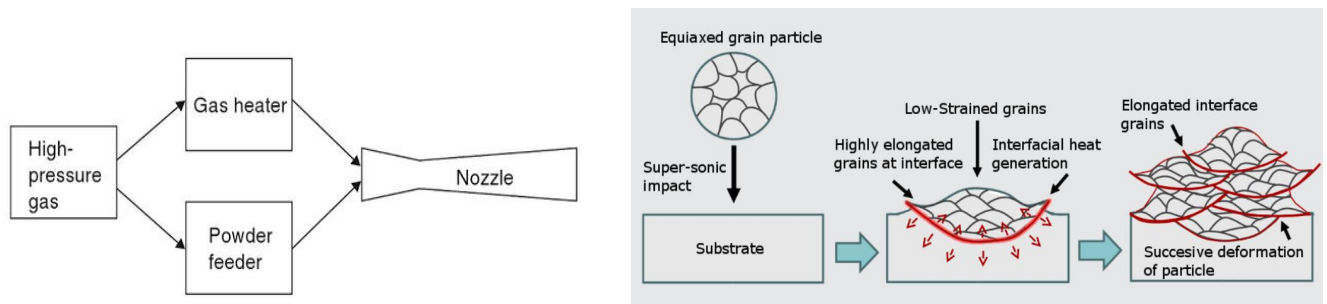


Figure 14. A schematic of the cold spray process (Left) and schematic of the layer build up during cold spray (Right). (Kang, Won, Bae, Ha, & Lee, 2012)

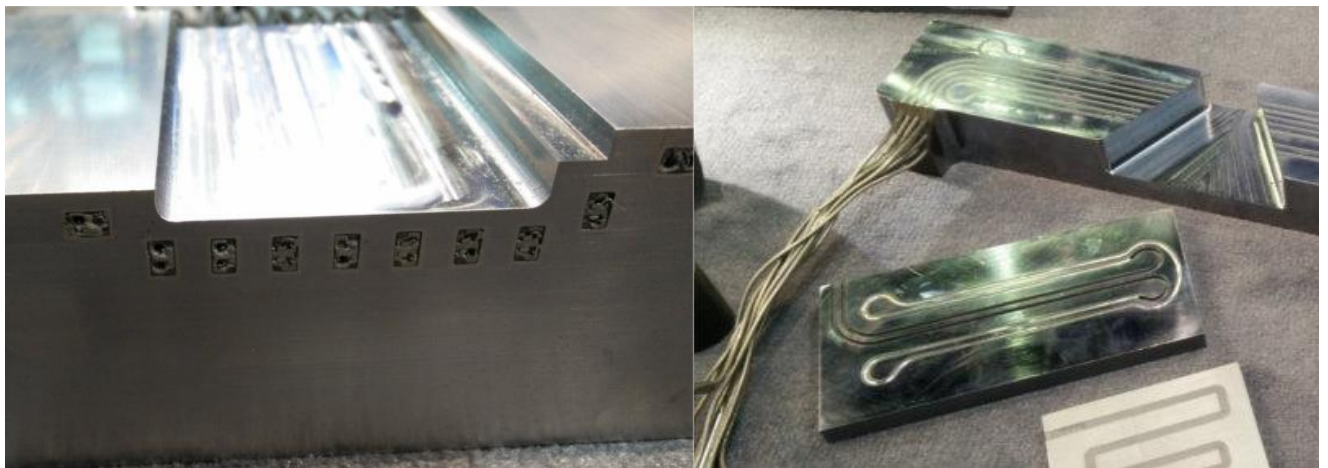


Figure 15. Parts manufactured with Cold spray hybrid systems with internal channels and embedded wiring.

Technology comparison

Several characteristics of L-PBF, DED and hybrid technologies are compared in Table 1. The table represent the typical values for each technology.

Table 1. Comparison table for DED, L-PBF and hybrid manufacturing processes.

Characteristics	DED (powder)	DED (Wire)	L-PBF	Hybrid: DED	Hybrid: L-PBF	Hybrid: Cold spray
Heat source	Laser, plasma-arc	Laser, plasma-arc	Laser	Laser, plasma-arc	Laser	No heat source
Maximum power output	5 kW	Laser: 5 kW	1000 W (Typically: 200-400W)	Laser: 2 kW Plasma-arc: 30 kW	1000 W (Typically: 200-400W)	-
Atmosphere	Inert	Inert	Inert (Argon, nitrogen)	Inert	Inert	Air
Raw material form	Powder	Wire	Powder (Gas atomized)	Wire/Powder	Powder (Gas atomized)	Powder
Multi-material	Possible	Possible	No	Possible	No	Possible
Number of commercial materials	large	large	Limited (expands rapidly)	Limited	Limited	Limited
Part dimensions	Limited by process chamber	Limited by process chamber	Limited by process chamber	Limited by process chamber	Limited by process chamber	Limited by process chamber
Build chamber size range	200x200x200 mm ³ - 4000x1000x1000 mm ³	1100x1400x1400 mm ³	50x50x80 mm ³ - 800x400x500 mm ³	735x650x560 mm ³	250x250x185 mm ³ - 600x600x500 mm ³	N/A
Part complexity	limited	limited	Almost unlimited	limited	Almost unlimited	limited
Min. wall thickness	≥ 1 mm	≥ 1.5 mm	≥ 0.1 mm	≥ 1 mm	≥ 0.1 mm	≥ 1 mm
Deposition rate	up to 500 cm ³ /h, typically 100-200 cm ³ /h	up to 500 cm ³ /h, typically 100-200 cm ³ /h	Single laser: 10 - 25 cm ³ /h Multilaser: up to 100 cm ³ /h	-	Up to 35 cm ³ /h	Up to 200 cm ³ /h
Typical layer thickness	250 µm	3000 µm	20 - 50 µm	-	20 - 50 µm	-
Part density	≥ 98 %	≥ 98 %	≥ 99,5 %	≥ 98 %	≥ 99,5 %	≥ 99 %
Surface finish	-	-	5µm ≤ Ra ≤ 20µm	Ra ≈ 1µm	Ra ≈ 1µm (machined)	-
Material cost	10 – 400 €/kg	2 – 200 €/kg	Commercial AM powder: 60 (SS) - 500 (Ti64) €/kg	10 – 400 €/kg	Commercial AM powder: 60 (SS) - 500 (Ti64) €/kg	20 - 1000 \$/kg
Machine cost	200 – 500 k€	200 – 500 k€	164 k€ - 1,6 M€	-	550 - 1200k€	N/A

2.4 General safety aspects in AM

Safety issues should be given a high priority in the design and operation of AM facilities. The use of AM has increased rapidly in research institutions, universities and industry, who have to consider the safety issues in designing safe and functional work facilities and environment.

There are safety guidelines and fact sheets available that contain information for assisting manufacturers to identify the appropriate safety standards and associated regulations for example the 3D printing & AM equipment compliance guideline (UL, 2015), the safety management guideline (UL, 2016) and the guidelines published by the the Finnish Institute of Occupational Health ((Työterveyslaitos, 2016).

Some important factors to consider regarding identification of standards and regulations for industrial application of AM technologies:

- Operating environment (factory, office, etc.)
- Intended type of user/operator (skill level)
- Technology specifications (laser, EB, UV, etc.)
- Raw materials (form, toxicity, by-products, waste, dust)
- Regional regulatory requirements for specific applications (if exists)

Aside from guidelines there is little information available regarding the design and safety of facilities used for metal AM. Carnegie Mellon University published a study on the safety and workflow considerations for modern additive manufacturing facilities where they report on their experiences on constructing a new metal additive manufacturing research laboratory using primarily powder materials (Scime, Wolf, Beuth, Mrdjenovich, & Kelley, 2018). Their main results regarding health and safety considerations and workflow are the following:

Health and safety considerations:

- Most metal powder should be stored in auto-closing flammable cabinets located in an area with improved fireproofing.
- A class D fire extinguisher or other non-water-based systems is required in case of fires fueled by reactive powders such as aluminium.
- Electrostatic dissipative (ESD) flooring and ESD shoe straps should be used to reduce the risk of fires caused by electrostatic sparks.
- Operators should use full-face P100 respirators or equivalent protection when powder is exposed to the environment to avoid the possibly harmful exposure to powders.
- Metal equipment used for handling metal powders should be placed in a separate room equipped with higher air exchange rate and access controls.
- Spilled powder should be cleaned immediately. The use of black flooring is advised as it improves the contrast of spilled powder and makes it easier to detect.
- Oxygen sensor should be mounted below the head height to warn the operators of gas leaks.
- AM processes generate hazardous waste such as unused powder, filters, solvents, glues and petroleum products. Proper procedures for the disposal of large quantities of this waste should be in place. Also emergency eyewashes and showers may be required.

Workflow

- The facility where powder materials are handled should provide sufficient climate-controlled storage capability
- Ancillary equipment and other heavy equipment are required for AM that need to moved around the facility. This should be accounted for in the floor plan design.
- The relevant post-processing equipment should be located near the AM machines to reduce the risk of damaging the parts during transport.

2.5 Current status of standardization in AM

The purpose of standards is to provide a uniform set of methods, processes and practices that allow industries to operate and report results effectively. A widely identified barrier for the more broad adoption of AM technologies is the lack of related standardization. The standards currently applied to conventional manufacturing processes and materials are not always suitable for AM. (Monzón, Ortega, Martínez, & Ortega, 2014) Lack of standardization has been identified in the topical areas of design, process and materials (precursor materials, process control, post-processing, and finished material properties), qualification and certification, non-destructive evaluation, and maintenance (America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC), 2017). Also the importance of AM product traceability in the event of product failure has been emphasized.

International Organization for Standardization (ISO), American Society for Testing and Materials (ASTM) and technical groups and projects are taking actions to develop the standardization for AM. ASTM formed a Committee on additive manufacturing technologies in 2009 called F42. It consists of experts mainly from USA and Europe and its objective is to promote the knowledge, simulate research and implement technologies through development of AM standards. The F42 has subcommittees for test methods, design, materials and processes, executive, terminology, strategic planning and ISO TC261, which is a committee on Additive manufacturing technologies formed from 16 participating countries and 5 observer countries. The objective of the TC261 is to provide standardization for fundamental aspects of AM and it has four technical subcommittees that are terminology, methods, processes and materials, test methods and data processing. They are developing standards solely for AM but also adopting existing standards that are seen useful. (Monzón et al., 2014). In Table 2 are listed the AM-standards approved by ASTM F42 and ISO. Many more draft standards are under preparation.

Table 2. List of published AM-standards. (ASTM, 2018).

Designation	Title
Design	
ISO / ASTM52915 - 16	Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2
ISO / ASTM52910 - 1	Standard Guidelines for Design for Additive Manufacturing
ISO / ASTM 52910 2018	Additive manufacturing — Design Requirements, guidelines and recommendations
Materials and Processes	
F2924 - 14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
F3001 - 14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
F3049 - 14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
F3055 - 14a	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
F3056 - 14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
F3091 / F3091M - 14	Standard Specification for Powder Bed Fusion of Plastic Materials
F3184 - 16	Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion
F3187 - 16	Standard Guide for Directed Energy Deposition of Metals
F3213 - 17	Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion

Designation	Title
F3301 - 18	Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion
F3302 - 18	Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Titanium Alloys via Powder Bed Fusion
F3303 - 18	Standard for Additive Manufacturing – Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications
F3318 - 18	Standard for Additive Manufacturing – Finished Part Properties – Specification for AlSi10Mg with Powder Bed Fusion – Laser Beam
ISO / ASTM52901 - 16	Standard Guide for Additive Manufacturing – General Principles – Requirements for Purchased AM Parts
Terminology	
ISO / ASTM52900 - 15	Standard Terminology for Additive Manufacturing – General Principles – Terminology
Test Methods	
F2971 - 13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
F3122 - 14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
ISO / ASTM52921 - 13	Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies

As of March 2017, 10 work items were under development. Among them were specifications for material traceability. In 2016 America Makes and the American National Standards Institute (ANSI) launched the America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC) with the objective to coordinate and accelerate the development of the additive manufacturing standards and specifications to support the growth of Additive manufacturing Industry. In 2017 AMSC published a Standardization Roadmap for Additive Manufacturing, which was developed in a joint collaboration of stakeholders including OEMs, industry, government, academia and SDOs to recognize the needs for the future of standardization for Additive manufacturing. (America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC), 2017) They identified 89 gaps in the standards, where a gap means that the specific issue is not covered by an existing standard. They also gave recommendations to remove the gaps. The actions taken by the AMSC are an important step towards more coherent and comprehensive standardisation in the industry and AM community in general.

3. Integration of AM into production systems

3.1 Control technology of AM machines

In general, control technology of the AM machines is very similar to other industrial devices. Powder handling and laser technology are the most unique features of the AM machines. Laser related technology, e.g. laser transmitters, beam deflection and focusing system, are provided by manufacturers specialized for laser and optics. Otherwise AM machines typically consist of a common industrial components; servo motors and drives for handling movements (e.g. powder bed and position of the building platform), a PLC (programmable logic controllers) for controlling the machine and IO-modules for reading sensor signals. As a user interface an industrial PC with touch panel is a common feature. A schematic of the main control features in AM machines is shown in Figure 16.

AM machine can consists of several interconnected units and be based on a modular architecture. Possible units of the AM machine are a powder handling and recycling units,

building chambers and a handling station unit with various functions such as unpacking, parts cool down, powder removing and recycling, heat treatment, product removal and product storage. In some systems several can be included in one machine enabling continuous operation.

For communication between different units industrial bus systems such as PROFINET or EtherCAT are used. Also connections to the outside world, either to the network of the plant, or to the internet exist. These are utilized to various tasks such as remote monitoring of operation, remote maintenance or control of production, e.g. downloading job files to the machines. Control software is an important part of the AM machine and all machine manufacturers have their own manufacturer specific software as well as remote monitoring and remote maintenance services.

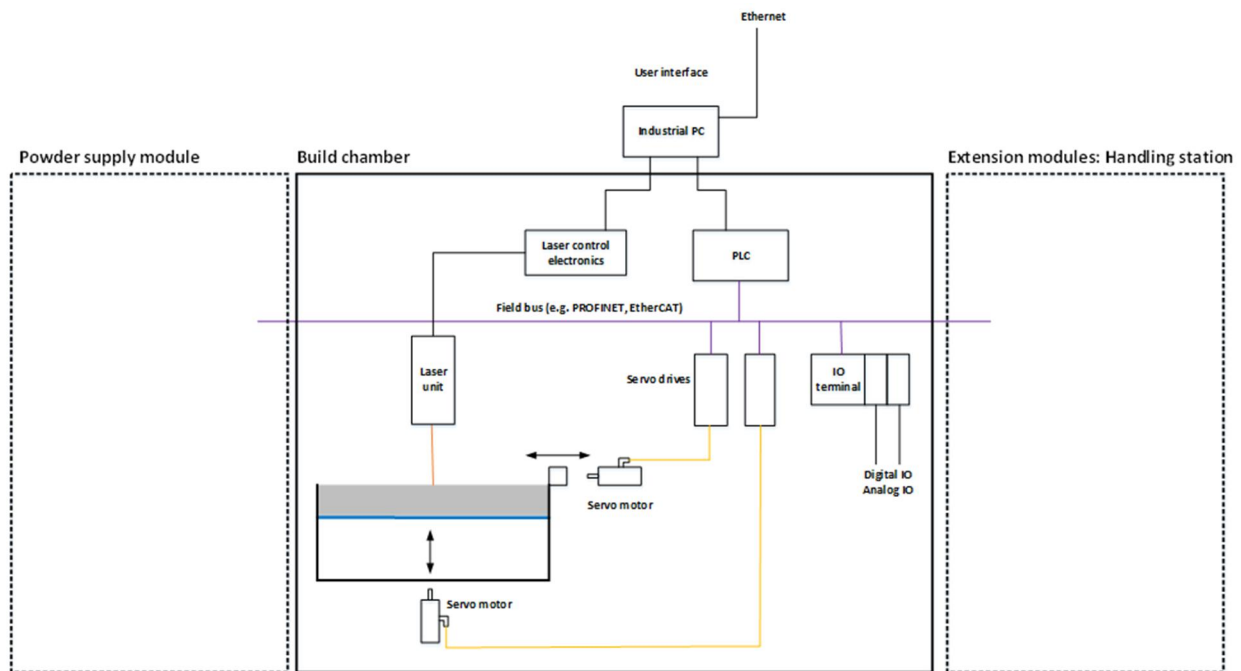


Figure 16. Main control components of the AM machines.

3.2 AM as part of the production system

AM machines are already equipped with internet connections. AM machine manufacturers provide software and services for remote monitoring, reading real time status, logging variables, managing manufacturing queue and loading jobfiles to machine. Also live video and thermal images are utilized and there are special systems for meltpool monitoring and powder bed monitoring. This kind of technical features form a good basis for integration AM machines as a part of the production system.

Since AM machines are build using common industrial components from manufacturers like SIEMENS, Bosch, Beckhoff or Schneider, they also benefit from the development of the industrial IoT and standardization. For example SIEMENS is doing co-operation with several AM machine manufacturers and SIEMENS hardware is used by several companies, e.g. EOS, DMG Mori, Stratasys, Gefertec, ADIRA and Vader. Industrial standards like machine to machine communication protocol OPC Unified Architecture (OPC UA) are commonly supported and connections to Enterprise Resource Planning (ERP) systems are also available in AM world.

In principle technology exists, but it is not widely utilized for integration of AM to production system. Main challenge for the integration is, that most AM devices are still designed as a stand-alone devices. One reason is, that in the past AM has been utilized to manufacturing prototypes and very small series and AM manufacturing process itself still consists of a several manual phases, that have been challenging to automate. Needs of the end-users are the main driver for developing AM machines and until now the main focus of the development has been on the AM technology itself, not in the integration to production systems.

Driver for integration is serial production. When AM is applied more and more to serial production, needs for the integration are increasing. AM machines are evolving from a stand-alone machines to a networked production machines. Main AM manufacturers are already developing AM machines that are capable of more autonomous and unmanned operation. Automation and robotics is also applied to previously manual pre-processing phases:

- Powder handling and recycling can be almost fully automated using powder sieving and handling stations. Powder containers are transported and handled by robotics and AGVs (Automatically Guided Vehicles).
- Continuous printing operation is enabled with a removable building chambers. Building chambers are handled by robotics or AGVs.
- External post-processing stations are used for serving several 3D printing machines.
- More automated post-processing; Tasks like removing and recycling of powder, removing parts from the building platform or heat treatment, are under development.

Automated post-processing is the area, where integration to the production systems is especially useful. AM should be synchronized with the following phases like machining, grinding and polishing.

3.3 AM process development towards integration and serial production

FormNext fair is an international fair focusing on AM. It is currently the biggest AM related event in Europe with 470 exhibitors and over 21 000 visitors in year 2017. In the fair biggest AM device manufacturers presented their new and coming products as well as their plans and concepts for the future. Here are some interesting examples from a perspective of integration.

In Figure 17 and Figure 18 concepts for autonomous operation of AM production by EOS, Trumpf and GE additive are presented. The common feature of these concepts is, that AM device works as a one unit in an automated factory and robotics and AGVs are used for supporting continuous operation of AM machines. Separate power handling units and post – processing units can serve several AM machines. There can be storages for building chambers and separate stations for manual phases (e.g. final cleaning of parts, removing supports), where these phases can be done without interfering the automatic AM operations. This approach fits very well together with the currently available Flexible Manufacturing System (FMS) technology.



Figure 17. AGV concept from EOS (left) and Robotic handling of powder containers and building chambers by Trumpf (right).

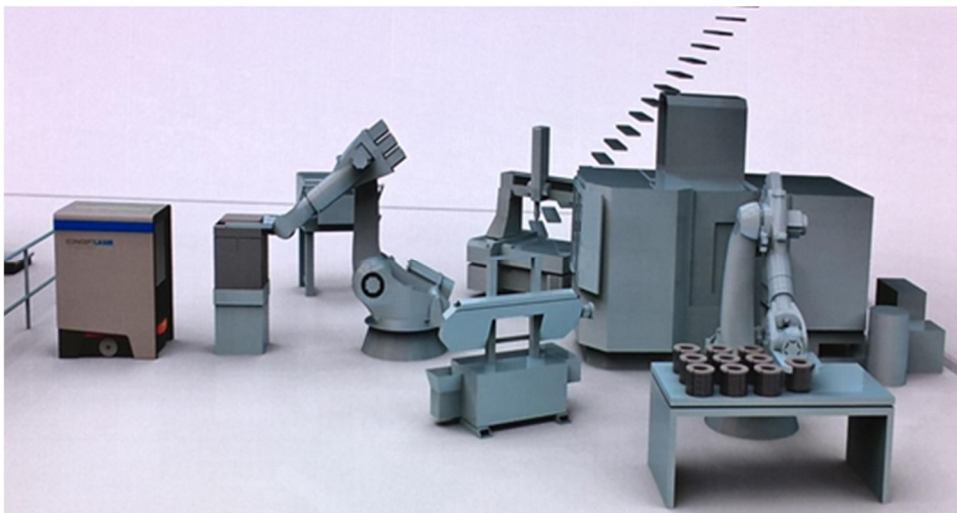


Figure 18. Factory of the future concept by GE Additive.

As an example of AM machine developed for a serial production, MetalFab1 machine by Additive Industries is presented in Figure 19. Dutch company Additive Industries has taken a different approach than other AM machine manufacturers and integrated several phases of the AM process to a one machine. The concept is based on modules, that can be connected together to form a complete AM production cell. MetalFab1 consists of control module, 2-4 AM cores (building chamber modules), heat treatment module, product removal module, storage module and an exchange module. On the back side of the machine there is a handling robot, that moves building plates from one module to another. Product removal module is the latest addition to the MetalFab1 modules. This module uses a band-saw to remove printed products from a building plate and then uses milling the resurfacing the building plate without any user intervention. With the aforementioned features a MetalFab1 device can execute multiple building jobs almost autonomously with little or no intervention from the user.



Figure 19. All-in-one AM manufacturing cell MetalFab1 by Additive industries.

Based on the discussions, presentations and demonstrations in the FormNext 2017 fair, the most significant AM machine manufacturers e.g. EOS, Trumpf and GE are investing to development of automation of post-processing phases to reduce manual work and to make AM more suitable for serial production. Additive Industries from Netherlands already introduced a new product, a product removal module, which is an addition to their modular MetalFab1 machine and enables almost autonomous operation. In the future AM will be more cost-effective choice for serial production too.

4. Product design (industrial design cases)

Continuous advancement in additive manufacturing, including available technologies, materials, design tools, etc. has meant that the range of components and products that might benefit from its use is also continuously expanding, whether that be during prototyping or production. However, there are a large number of interdependent factors that must be considered when choosing whether or not AM is a financially viable option. The following section discusses some of these factors.

4.1 Manufacturing considerations

Cost

The cost of manufacturing can be divided into fixed costs and recurring costs. Fixed costs are defined as costs that are not dependant on the units sold and these include buildings, tools, machines, etc. The recurring costs, that are associated with the produced units, include direct labour, material, maintenance, etc. Conventional manufacturing typically has higher fixed costs than AM due costs related to tools, dies and manufacturing floor space but lower recurring costs due to higher AM material costs (Frazier, 2014). There are multiple sources of waste costs in manufacturing processes that are a result of overproduction, transportation, rework/defects, over-processing, motion, inventory and waiting. These different factors increase the overall cost of the supply chain and should be minimized. Additive manufacturing can have a tremendous impact on many of these factors, such as overproduction and inventory as the only the required amount of parts can be printed on demand thus eliminating the need for large inventories. (Thomas & Gilbert, 2014)

The cost structure of AM has been analysed in literature (Lindemann, Jahnke, Moi, & Koch, 2012) and at VTT and according to the calculations, the major cost drivers for the process are machine related costs and material cost. The material costs are higher for AM than for traditional manufacturing as the raw material is often tailored for a specific process and produced in smaller quantities (Thomas & Gilbert, 2014). However the increase in AM material production volumes due to higher demand can be seen as lower prices. The cost estimation for AM production should take into consideration all the different steps that generate costs, that are related to design, manufacturing (including post-processing) and warehousing/logistics. It is important to understand how the type of the part, batch size, material, AM machine capabilities and post processing needs impact the total cost of the product. The post-processing phase can be a significant cost factor since practically all metal AM parts require some post-processing steps. Typically AM can be considered advantageous over traditional manufacturing if it makes the manufacturing previously impossible designs possible.

Materials

The material portfolio of AM has been growing steadily since the commercialization of the technologies. Currently the metal material groups available for additive manufacturing include tool steels, stainless steels, titanium alloys, commercially pure titanium, aluminium alloys and commercially pure aluminium, nickel-based alloys and pure nickel, copper based alloys and pure copper, cobalt-chromium alloys, precious metals and also hard metals and superalloys. The raw material requirements depend on the AM technology, but for powder based technologies the powders are mostly manufactured by atomization techniques (gas, water). The material selection is still narrow compared to what is available as cast and wrought form but with the increase in demand the suppliers are bringing more materials to the market.

Also the structural integrity of AM parts is a big concern for many companies and the fact that different AM technologies result in different material properties only adds to the confusion. The mechanical properties of AM parts are being studied extensively and it is apparent that in some cases the AM material have equal or higher strength compared to cast and wrought materials. Some properties such as fatigue strength however require more research to increase the confidence in AM materials.

Other considerations

In addition to cost and material considerations the design, post-processing and quality aspects of AM should also be assessed. The design related issues are discussed in more detail later in the report.

4.2 Digital spare parts

The digital spare parts concept has been described as those spare parts for which the related data are stored and transferred digitally. When need arises, the manufacturing of the spare part is done close to geographical location of the end user utilizing AM techniques. When making the economic case for 3D printing of spare parts, comparing just the costs of manufacturing between traditional and additive techniques only covers part of the story and would typically indicate that use of AM is economically infeasible. However, a look at the larger picture shows that spare parts costs are also incurred through storage, delivery, costs of lost or broken tooling and molds, and through downtime of equipment (Salmi et al., 2018).

There is also opportunity available when converting spare parts to digital storage and additive manufacture in the possibility for upgrading. Minor redesign of the spare parts can make it possible to add small customizable details such as product identifiers or logos, etc. More extensive redesign of spare parts can also be made to integrate sensors during or after

printing for remote monitoring, optimize for weight reduction, or reduce part counts in assemblies by consolidating several simple parts into a single more complex object.

4.3 Geometric freedom

Harnessing the geometric freedom that AM offers compared to traditional techniques is one of the key challenges in unlocking the benefits of this technology. With thoughtful planning on a carefully chosen component, additive manufacturing can help minimize use of material, add new functionality, improve performance, allow for smooth and intricate internal channels or cavities, or significantly reduce assembly part counts. Other than in the case of carefully chosen spare parts, it seldom makes sense to 3D print a component in the exact form that was originally designed for traditional manufacturing. In fact, an entirely new approach to design needs to be utilized, one that includes a deep understanding of the manufacturing limitations as well as the effect of design decisions on the whole manufacturing process (including post-processing, i.e. heat treatment, support removal, machining, surface treatment, etc.). This is at least partially due to the complex relationship between the accuracy and surface finish of a component, the geometry, and other process variables, which are in turn affecting production time, cost, and quality.

Design guidelines have been produced for the various additive manufacturing processes to help speed up knowledge transfer to designers. Various guide examples exist for e.g. SLM (ASTM/ISO, 2018; Kokkonen et al., 2016; Verein Deutscher Ingenieure, 2015), providing such information as minimum wall thickness and feature size (including both positive and negative volumes), angle for unsupported inclined surfaces and overhangs, self-supporting holes and channels, etc.

The geometric freedom offered by AM means that organic, freeform shapes can now be manufactured that may not have been possible previously. This has proven to be a challenge to CAD and simulation software providers who are scrambling to piece together offerings that cover all of design for AM (DfAM) needs, including:

- Advanced CAD features
- Design validation (e.g. FEM, CFD, MBD, etc.)
- Topology, size and shape optimization tools
- Lattice and infill creation
- Print preparation - parts nesting, support creation, printer-specific output
- AM process simulation
- Simulation of additional manufacturing processes, e.g. heat treatment, support removal, etc.

Along with the various additive manufacturing processes, the software tools supporting the design, simulation and preparation of the printed parts are changing at an extremely fast pace. Yet this year there should be several software providers offering most if not all of the features described in the list above, with at least reasonably straight-forward means to transfer the design data between the tools. In some cases, these tools may also be linked to product lifecycle management (PLM) systems.

Four component cases were provided by Sandvik for study within HYBRAM project (Figure 20). The idea was to investigate each case and determine suitability for additive manufacturing. The following gives an overview of the components, how they are currently manufactured, delivery time to the warehouse, number of pieces in stock and sold annually, and how additive manufacturing might be used to improve delivery times, performance, functionality, etc.

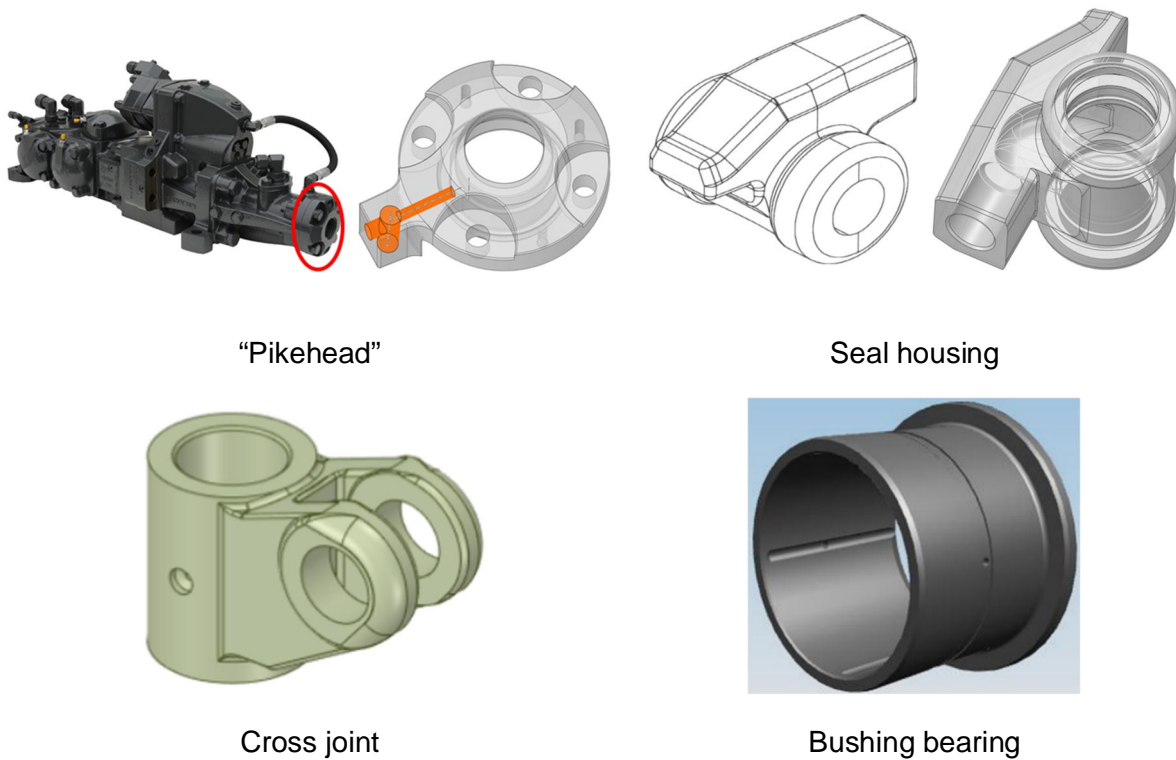


Figure 20. Four HYBRAM component case studies from Sandvik.

4.4 Case 1: “Pikehead”

The first case study was the so-called “pikehead” component that is positioned at the end of a rock drill and is housing a sensor and cable connection, as shown in Figure 21. The prototype design of this component currently costs approximately 200€ to produce, but the expected production price of the final design (by casting or forging) is expected to be under 100€. The main goal in considering this part for redesign and construction by AM is to improve the accessibility of the sensor, and to make a more smooth and protected connection point and path for the sensor cable to travel.

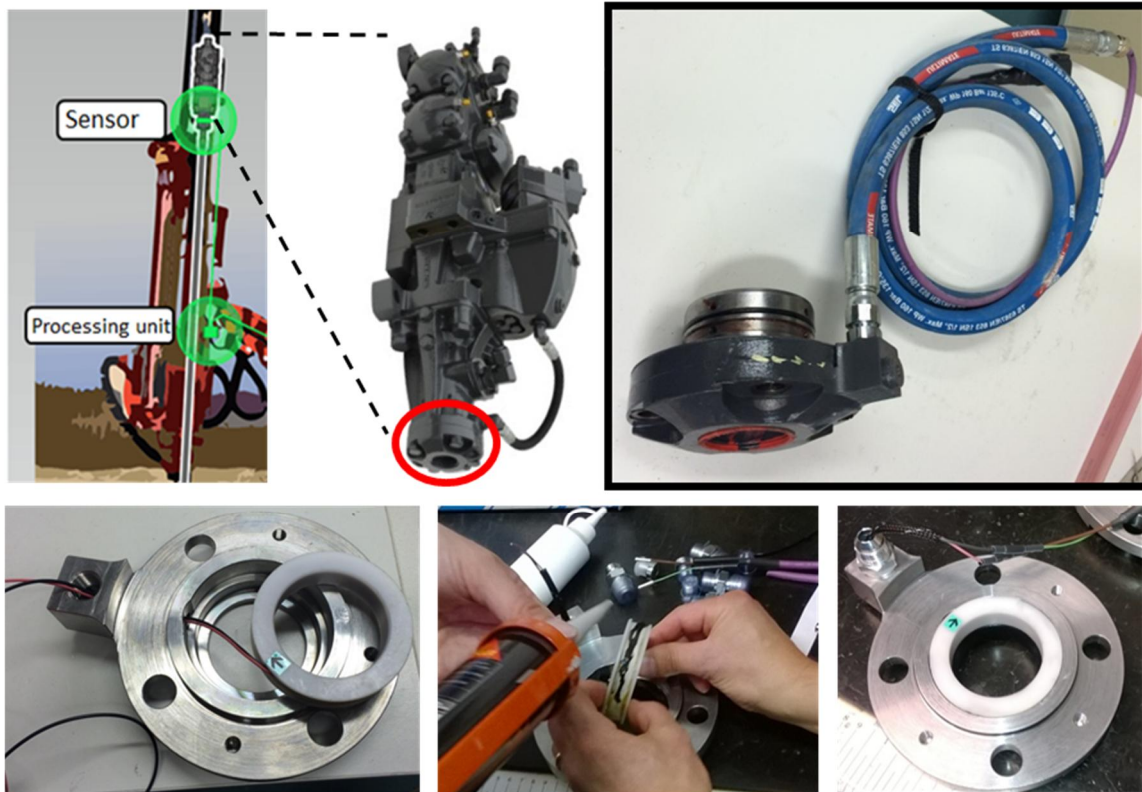


Figure 21. Original geometry of Sandvik 'pikehead' component shown at the end of a rock drill and during sensor installation.

Component redesign

This design case was studied closely during this project by Enmac Oy, with results presented in a separate report (Ahtiluoto, 2018). The main focus by Enmac was to modify the cable path within the component and then lightweight the product to reduce AM costs. Two main approaches were tested to reduce component weight - topology optimization and replacing part of the core volume of the part with lattice infill. Examples of the results from the report are shown in Figure 22.



Figure 22. Enmac Oy pikehead component redesign examples utilizing topology optimization and lattice infill (Ahtiluoto, 2018).

Additional AM design options

There were many design restrictions Enmac faced during the redesign process. The component is exposed to flying rock fragments, so a tough metal exterior is necessary to protect the sensor inside. The metal chosen must be corrosion resistant due to the operating environment. The neighboring components were not considered in the redesign effort, thus the component must fit in the assembly in the same way it does currently. The added expense of using L-PBF to additive manufacture the component with better positioning of the sensor cable will probably prohibit the uptake of this approach. An alternative, cheaper approach would be to combine manufacturing techniques by producing this part as done previously, but with a space reserved for a plastic 3D printed insert. A sketch of what this might look like is in Figure 23, with the blue component the region to be designed for the cable transfer and printed in plastic. The plastic part could e.g. be done in two parts that snap together after the cable is positioned.

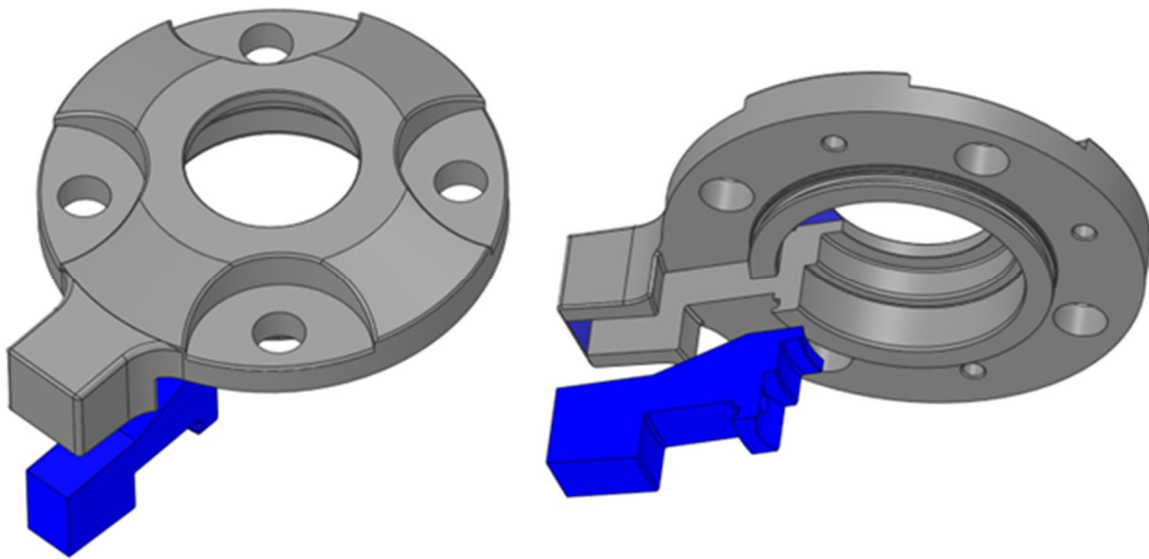


Figure 23. Original pikehead geometry (grey) minus a segment that is machined away and replaced with a 3D printed plastic component (blue) that includes a smooth channel for the sensor cable.

4.5 Case 2: Seal housing

The second design case considered was a seal housing, as shown in Figure 24. This part is typically made of cast and machined stainless steel (SS 2324-12), and costs 80€ to produce. Over 500 pcs. are sold annually, but this is a heavily pirated part so potential sales opportunity for the part are even higher.

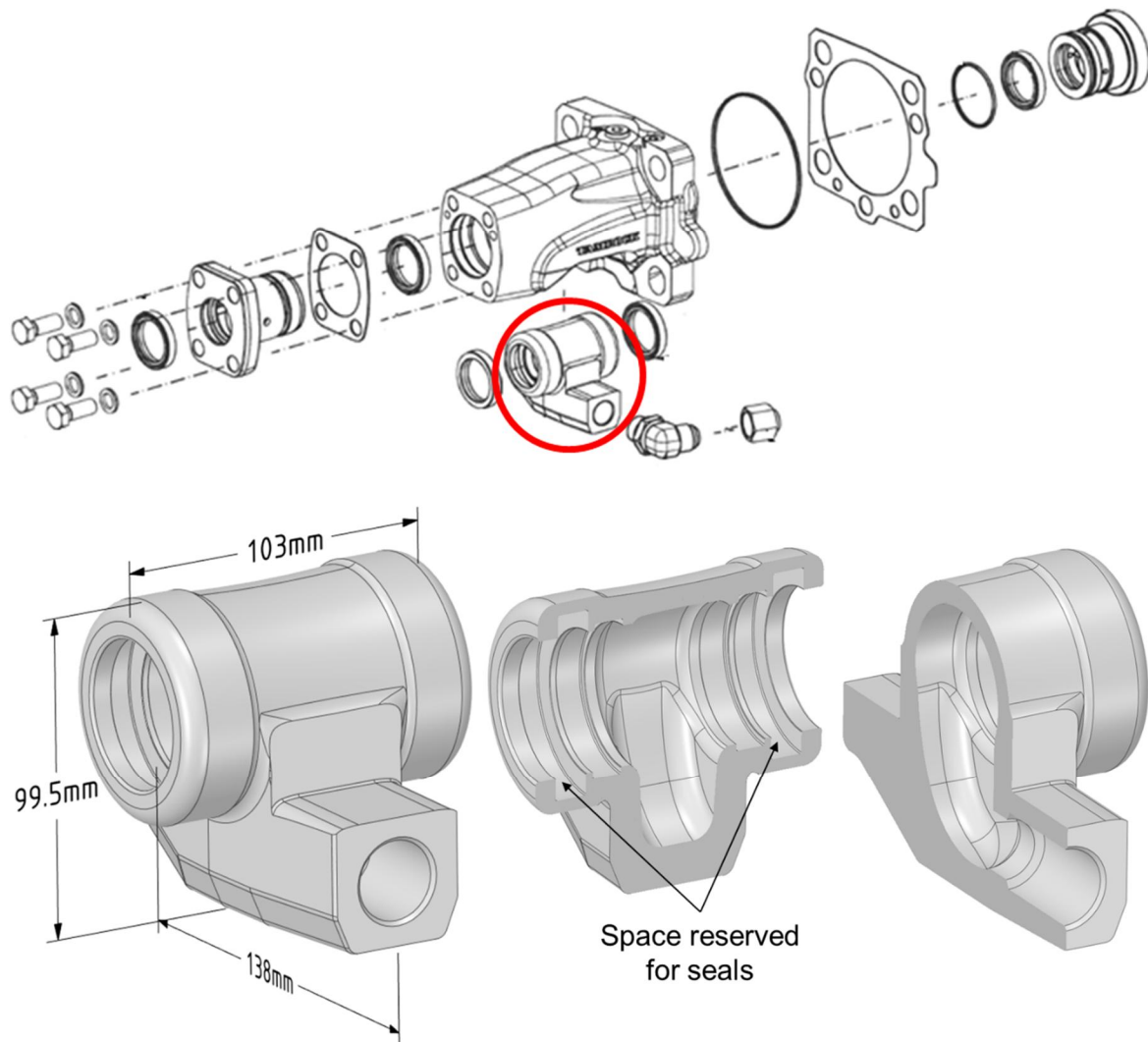


Figure 24. Original geometry of the Sandvik seal housing.

Print of original design - preparation, printing and post-processing

While there are many avenues that can be taken to redesign this part for improved performance by utilizing the design freedoms of AM (as discussed in §0), the creation of the original geometry of this part with AM was investigated as well. It was decided that the part would be created on VTT's SLM125HL in 316L stainless steel (properties found in Figure 50 of Appendix A).

The component was large compared to the build envelope of the SLM125HL, thus the possibilities for orientation and positioning the part on the platform were limited. Three example orientations of the component can be found in Figure 25, with the white box in the figures representing the print chamber volume and the red cylinders the platform bolt fixation points. In all three cases example orientations you will note that there is interference between the component and the red cylinders, indicating that if the part is printed as shown it would be impossible to remove the bolts and release the build platform from the printer. The first orientation Figure 25a, would have been preferred because having the large, dense layers near the base of the print would help the heat transfer away from the build layer later in the print. Unfortunately, two of the platform bolts would be completely covered by the component. Another option (Figure 25b) could be considered a good candidate because printing the large cylindrical region vertically would mean a huge reduction in needed internal

supports. However, a large amount of supports would be required to support the very dense section that includes the water intake channel. In this orientation the part does not entirely fit on the build platform. A final option, the one that was eventually chosen, is depicted in Figure 25c. In order to avoid the platform bolts, 4.5 mm of the solid back end (opposite the water intake) was removed for the test print.

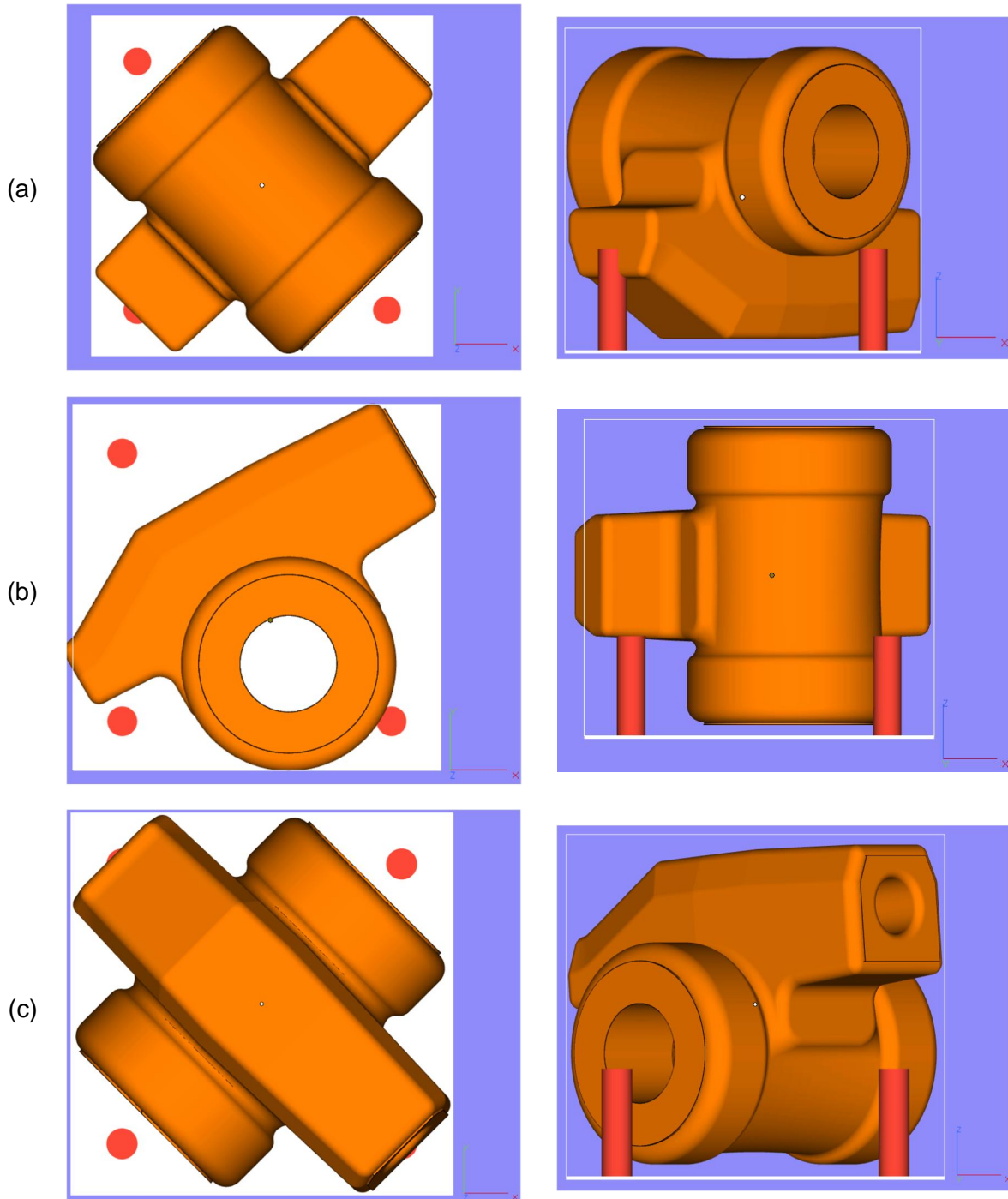


Figure 25. Possible orientations of the original seal housing component on the SLM125HL build platform; top view (left) and corresponding front view (right). The white box indicates the chamber volume and the red cylinders the platform bolt fixation points.

The final orientation of the part on the build platform and the necessary supports can be seen in Figure 26, along with photos taken after printing. You will notice in the top images in the

figure that special care was taken to create the supporting structures such that the platform bolts could be removed after the build.

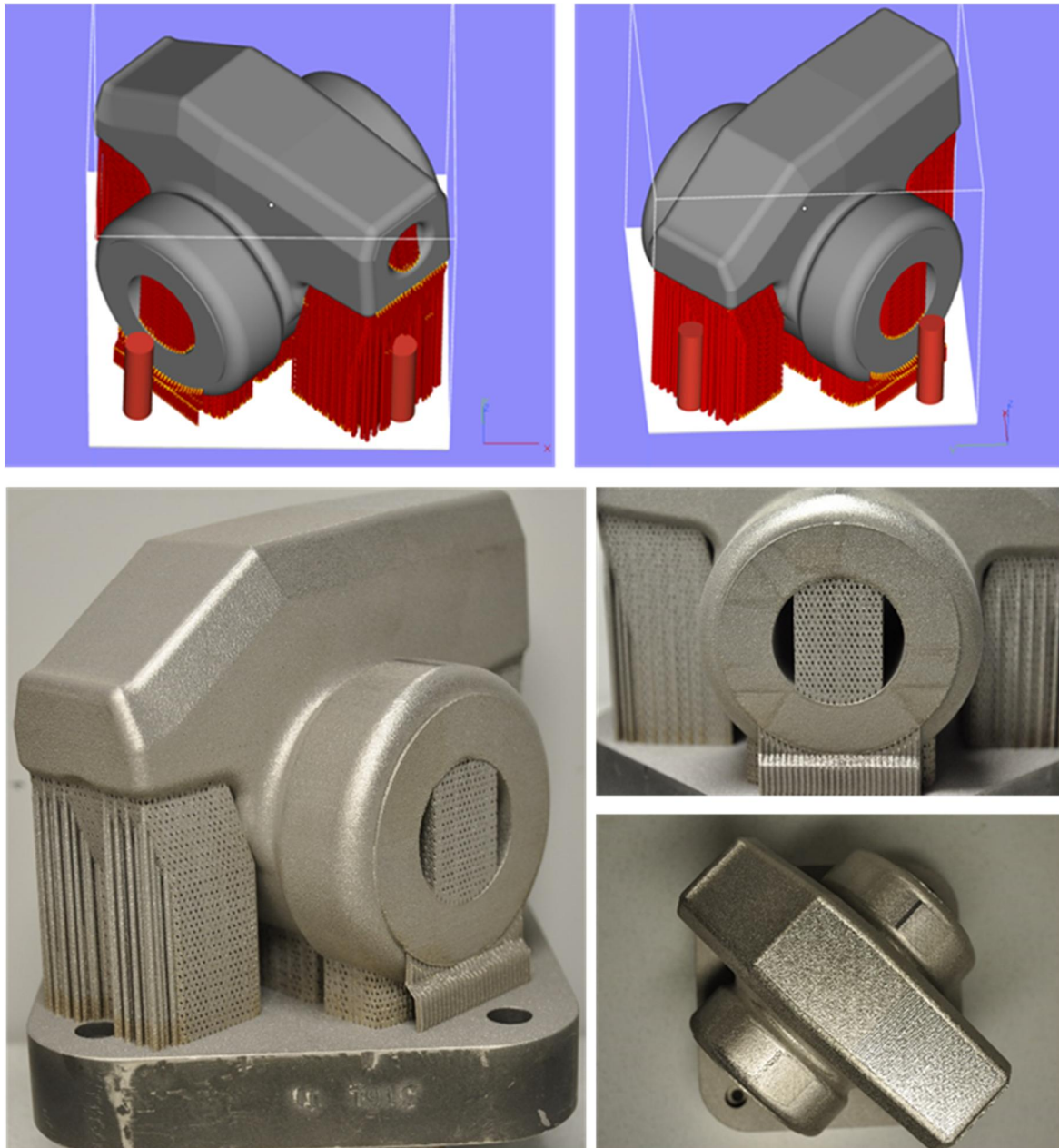


Figure 26. Original Sandvik seal housing positioned on SLM125HL build platform with necessary supporting structures and printed in 316L stainless steel.

When printing a component that is this large and with such dense regions, it is necessary to carefully control the heat transfer away from the printing layer during the build. Careful orientation and support design are necessary to prevent build failures, and process simulation tools can be used to help ensure a successful print. Figure 27 shows an example simulation used when preparing the original seal housing print.

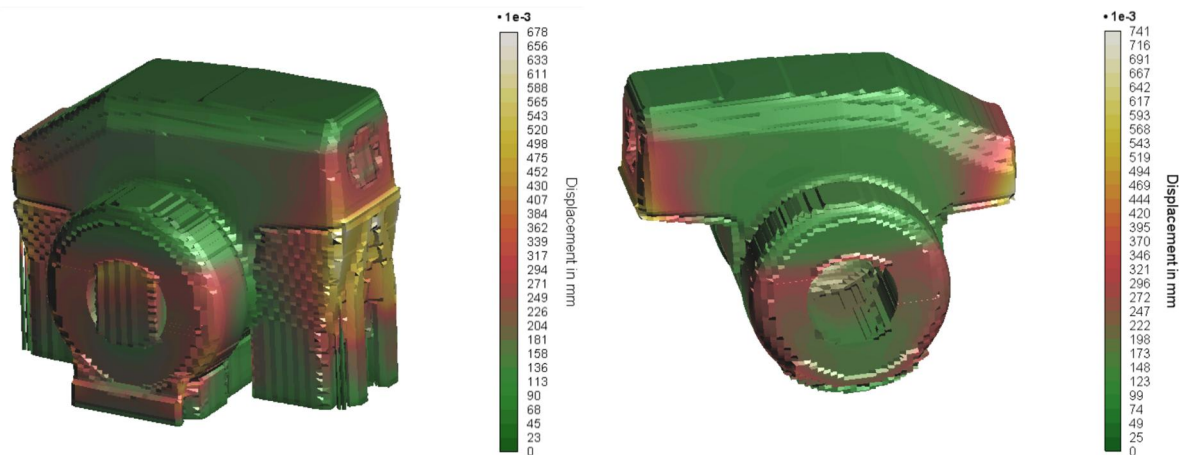


Figure 27. Simulated displacements of the original seal housing after print completion (left) and after support removal (right).

Component use and possible design modifications

The seal housing component is part of the flushing housing assembly of a Sandvik rock drill, as seen at the top of Figure 24. During operation, water (often seawater), water mist, or air runs into the seal housing at the inlet and exits through a radial hole in the drill shank which passes through the center of the housing. The component needs to withstand internal fluid pressure and external impacts, while also being corrosion resistant.

Several ways to potentially improve this component by utilizing the geometric freedom of AM have been identified. The first is to improve the performance of this part by increasing the lifetime of its two seals, as the machine downtime incurred when changing the seals leads to significant expense on the part of the customer (and depending on service and sales models, the cost may also be transferred to the component producer). The second is to find a means to reduce component piracy - the producer is losing millions of euros per year in component after-sales due to counterfeited parts. The third is to find ways to add functionality, e.g. sensor integration, such as that seen in the case studied in §4.4. And finally, after methods to improve performance and functionality have been identified, the part should be redesigned to minimize unnecessary material usage and for ease of manufacture.

While a full redesign of the seal housing was not possible within this project, some ideas for how the component could be improved were considered:

- Integration of non-contact type seals (e.g. labyrinth seals)
- Smoothing of internal fluid channel, with attention paid to printing direction so that the top surface of the channel can be made in such a way to reduce necessary supporting structures
- Hollow out the large, dense region behind the inlet and fill with e.g. lattice or gyroid structures to reduce component weight, heat build-up during printing, and to make counterfeiting more difficult (again printability should be kept in mind - use the lattice structure design to support the top surface of the cavity during the build rather than supports that cannot be removed, and include a hole for powder removal after printing)
- Sensor integration into the component for predictive maintenance of the seals

Some of these initial design ideas are demonstrated in Figure 28. Modifications to the external geometry of the part have not been suggested here as they would affect the design of neighboring components in the assembly. However, it is always advisable to consider the

potential of consolidating neighboring components of an assembly during AM redesign (Yang, Tang, & Zhao, 2015; Pour & Zanoni, 2017; Oha, Zhoua, & Behdad, 2018).

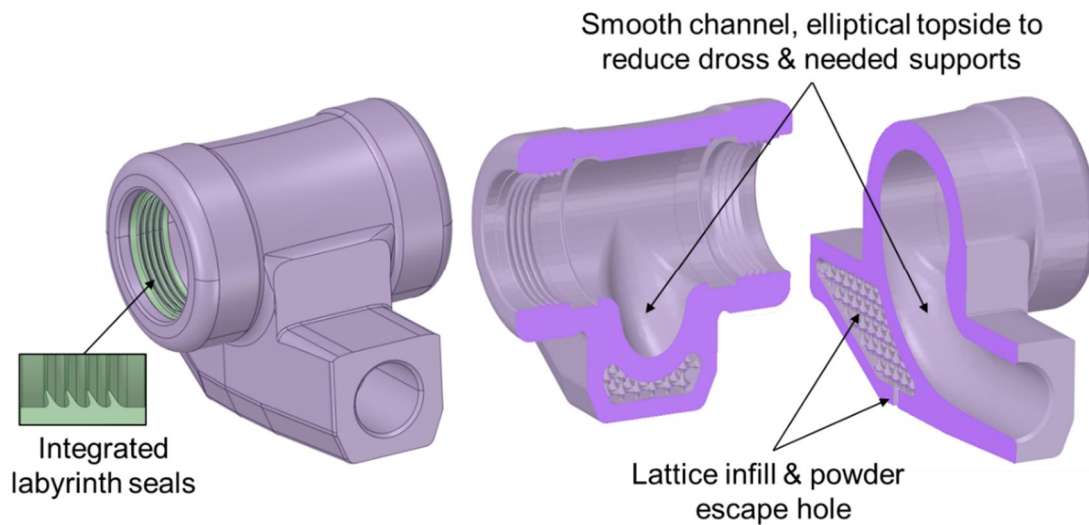


Figure 28. Seal housing redesign ideas.

Possible further work

In order to redesign the seal housing for production, extremely close cooperation is necessary between the Sandvik experts in charge of this product and assembly, AM design engineers who are familiar with the demands of the chosen manufacturing technology, and simulation engineers who can aid in the design of integrated seals with fluid flow calculations or verify the structural integrity of the redesigned component when reducing excess material. The possibility of integrating the seals into the design is an interesting prospect, but would require considerable work to optimize the design for the use case, determine the best manufacturing strategy, and carry out necessary testing. Luckily, the use of AM also in the prototyping phase tends to speed up this design-prototype-test process and allows for modifications or improvements to be considered at reasonable cost even late in the design phase.

4.6 Case 3: Cross joint

The third case studied was a SB60 boom cross joint, which is described in Figure 29. This component is sold as a 28 kg cast iron (En 1563 – EN-GJS 700-2) cross piece along with two tin bronze copper bushing bearings (described in §4.7). The manufacturing cost for the cross joint is 270€, with delivery to the warehouse taking approximately 4 weeks. An estimated 18 pcs. are sold per year, and 15 pcs. are kept in stock globally.

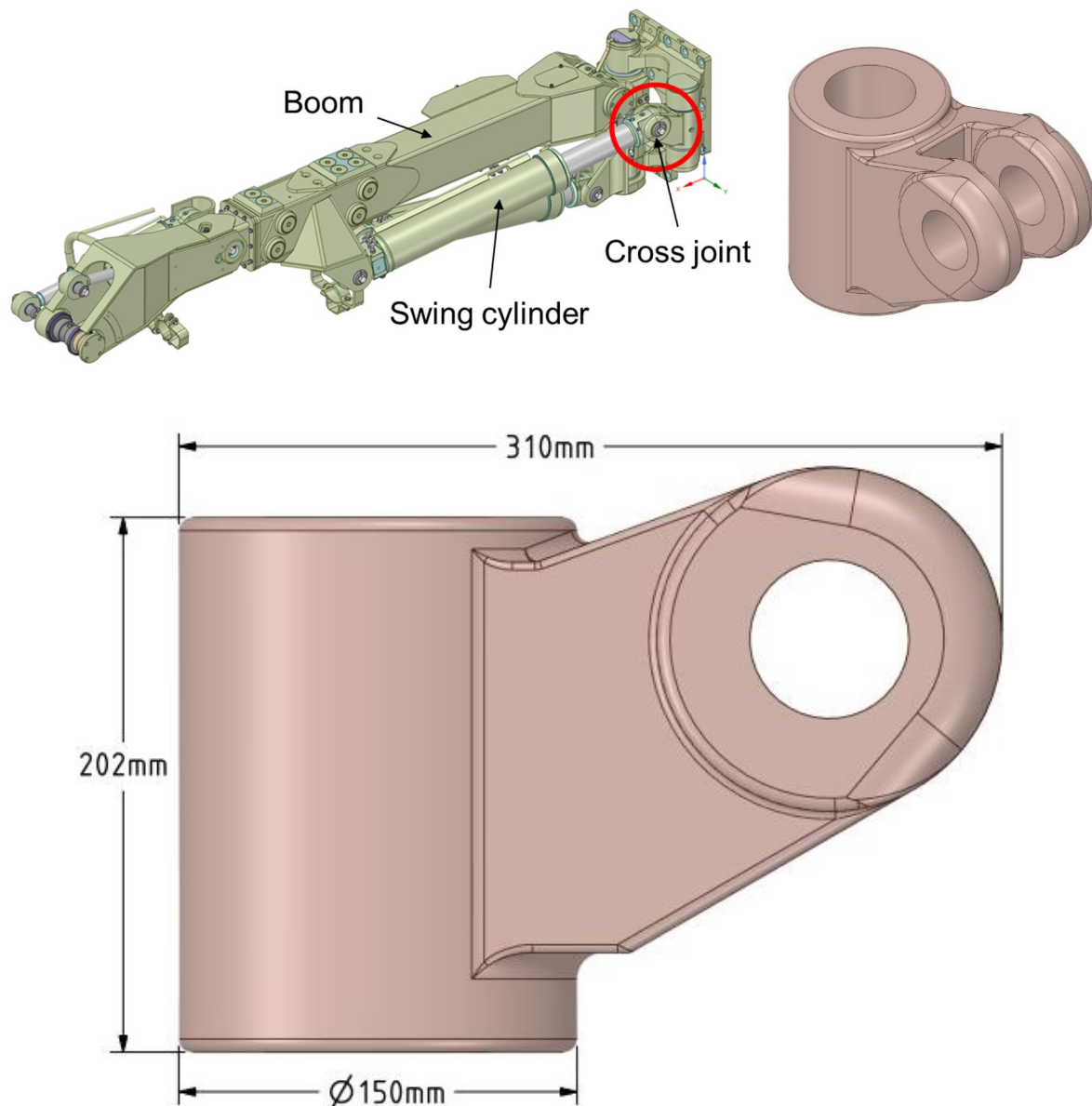


Figure 29. Sandvik SB60 boom (top left) and cross joint component.

Design approach

Due to the size and weight of the component, the cost of additive manufacturing this component by e.g. L-PBF is likely to be considerably more than the currently used casting process. It is possible that a component like this could be redesigned for AM to reduce weight, improve performance or functionality, to consolidate with additional parts of an assembly, etc., but for this particular product there is currently no pressing need for this. Thus we will look at this product as a potential candidate for a digital spare part (Salmi, et al., 2018) - i.e. that it can be printed on/near location and on demand.

Even as a digital spare part, time and cost of additive manufacturing metals is reduced as the size of the part is reduced. Thus, if a part's loading cases are known, finite element based topology optimization techniques can be utilized to predict optimal material usage (Liu & Ma, 2016; Pinto & Seabra, 2016; Walton & Moztaezadeh, 2017). For the cross joint, the primary load cases are indicated in Figure 30. A series of topology optimization cases were run with variations in e.g. volume fraction, stress limits, available design space, etc. During this preliminary design study, three material options were considered: H13 tool steel, 17-4PH

precipitation hardened stainless steel, and maraging steel (see material composition and properties in Appendix A.

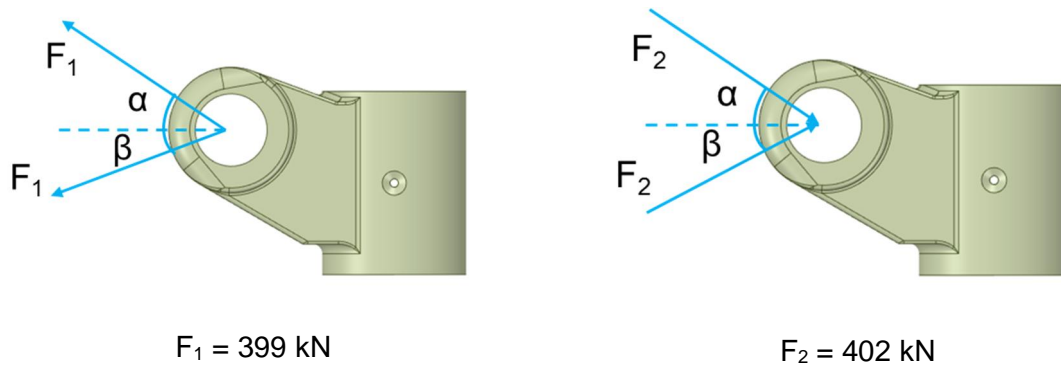


Figure 30. Primary load cases for the cross joint, with maximum angles $\alpha = 45^\circ$ and $\beta = -35^\circ$.

An example of one topology optimized result is shown in Figure 31. In this case the volume of the part was reduced by around 40%, having a weight of 16.6 kg for maraging steel, while a conservative factor of safety was maintained. With further design iterations, it is very likely that the size of the part can be further reduced.

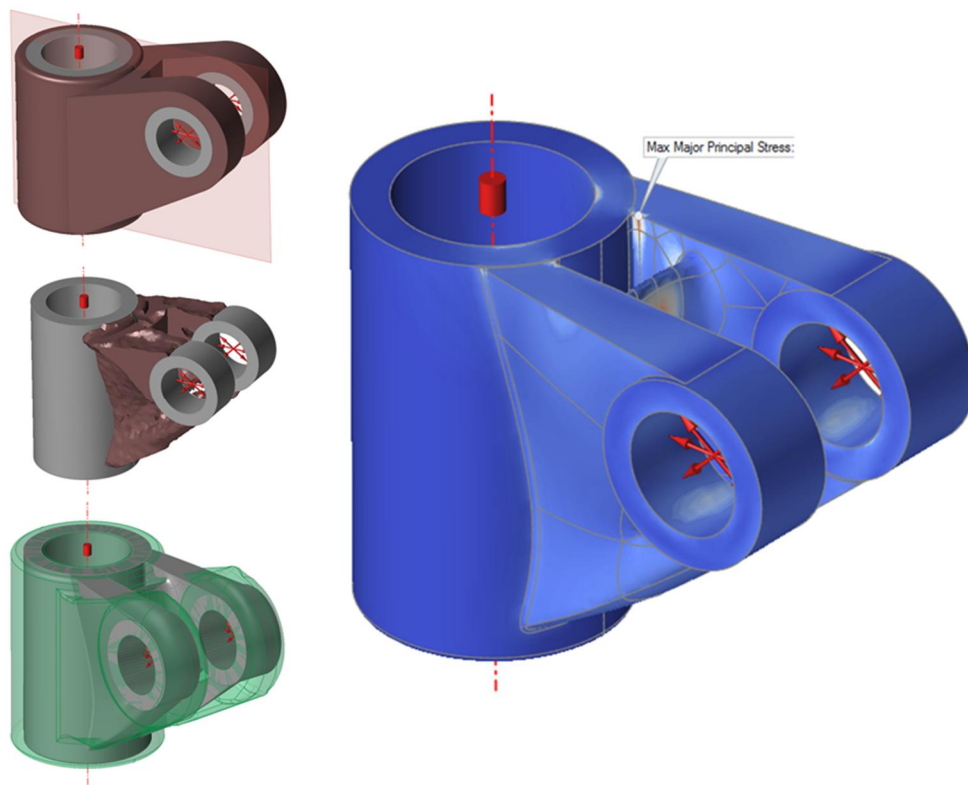


Figure 31. Example of topology optimization procedure on Sandvik cross joint component; including images of the design space, optimization result, smoothed result compared to original design volume, and reanalysis.

Manufacturing options

Using the presented topology optimization result, it is possible to compare some manufacturing methods for the cross joint. Below, production by L-PBF, DED, and 3D printing of sand molds for casting are considered.

Due to the size of this component, even after weight reduction, initial quotations for production by L-PBF in maraging steel were nearly 100 times the current cost to manufacture the part. Manufacturing the crossjoint using a large scale L-PBF machine equipped with 400x400x400 mm³ build platform and four lasers would mean that two parts could be printed at once with a build time of over 100 hours. The total manufacturing cost would consist mainly of material and machine costs, the latter comprising of the machine purchase cost & investment period, utilization rate, build volume and number of lasers as well as the maintenance cost. The material costs can be decreased by using topology optimized designs as described earlier. Machine cost, which is the most significant cost factor, can be lowered by increasing the utilization rate i.e. reducing the idle time of the machine. Despite the L-PBF option being time consuming and expensive at first glance, the possibility to manufacture the part on demand to avoid possible downtime costs could offer a real advantage.

A second method could be the DED method (Figure 32). In this case a focused thermal energy source can be either laser or arc plasma. Relatively large energy input can be used, because there is no need for adding detailed features and the amount of fused material is more important. Around 2 kg of material per hour can be added using plasma arc as an energy source. A DED machine can add features to the existing part.

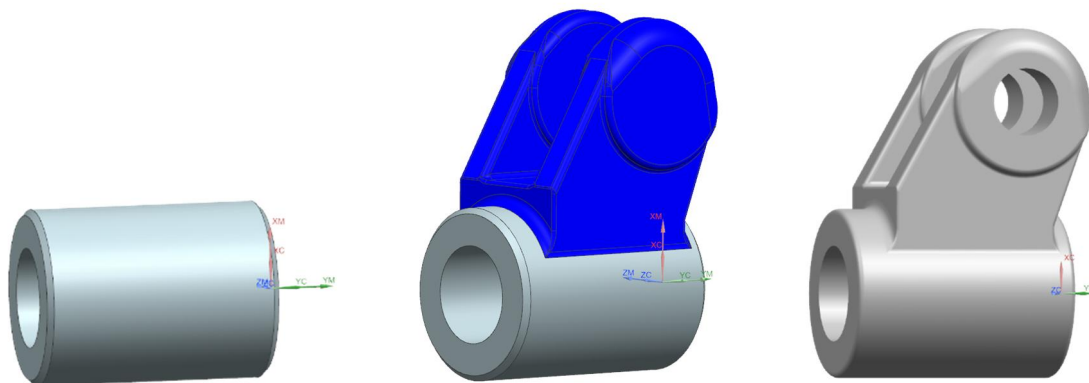


Figure 32. Example of DED process where traditional machining and additive manufacturing are combined. Non axial symmetric features are added to the existing part and then finishing is done with traditional subtractive methods.

The main part of the cross joint has axial symmetric, so it is profitable to manufacture the part with traditional lathe and then add the prismatic features with DED. The added features are not optimized and around 9 kg of material is added. The DED process takes 5 hours with some cooling times. DED material cost with stainless steel wire is roughly 10 €/kg. The manufacturing cost by DED is much less compared to L-PBF, but more still more compared cast and traditional manufacturing methods.

A third production method could be 3D printing of a sand mold and casting of the component (Komi, Kokkonen, Virta, Puukko, & Metsä-Kortelainen, 2017). This becomes a very interesting option in cases where very few parts are needed, component size is large, small amounts of customization are desirable, and tooling or molds for the component are lost or otherwise unavailable. Costs arising from the use of this technique include 3D printing of the

sand mold (~500€, depending on final size and whether expedited services needed) and then the typical casting and machining costs. If only the component geometry is available, then a mold design also needs to be created. This may take about a week at a typical engineering firm and if so, cost around 6000€. Again, the cost of the mold design and cast simulation can vary considerably based on component size, material, and amount of detail required for the mold.

4.7 Case 4: Bushing bearing

The fourth case studied was a bushing bearing that is used e.g. with the cross joint described in the previous case (Figure 33). This component is currently cast from tin bronze copper (En 1982 CuSn12-C) and weighs 2 kg in its final (machined) state. The manufacturing cost of this part is 44€, and delivery time to the warehouse is 3.5 weeks. Approximately 750 pcs. of this part are sold annually, with 140 pcs. maintained in stock.

This component has not been identified as one that could be improved through redesign, but rather one that has potential as a digital spare part. With this in mind, the plan was to:

1. Optimize the print approach to minimize post-processing and maximize geometric accuracy
2. Determine if any design modifications should be made to improve the result or reduce the cost

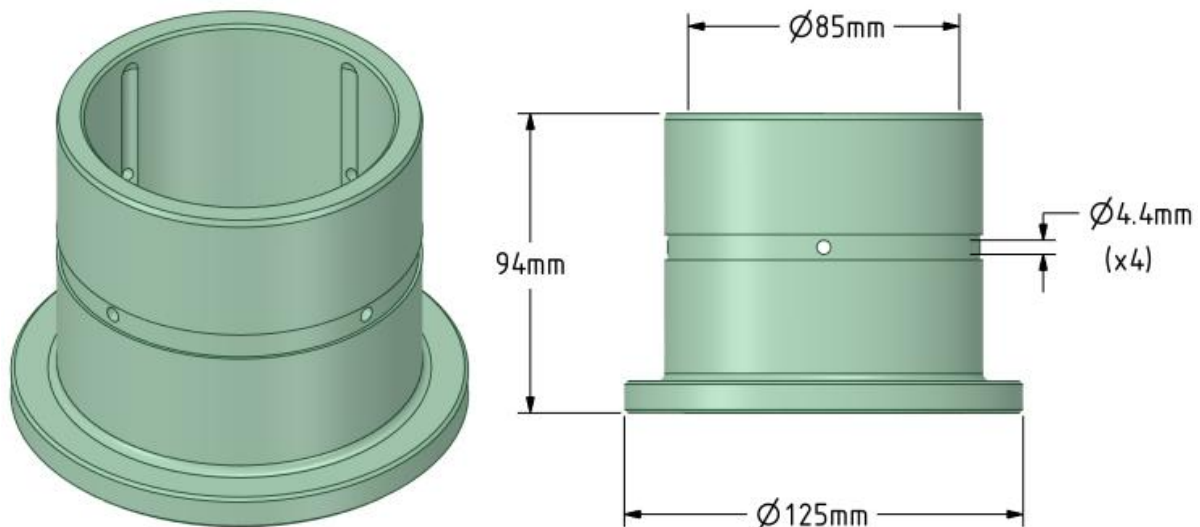


Figure 33. Original geometry of Sandvik tin bronze copper bushing bearing.

Print preparation to minimize post-processing

It was decided that the bushing bearing would be printed on VTT's SLM125HL using SLM's copper-tin alloy (CuSn10) powder. A summary of the powder makeup and properties can be found in Figure 54 within Appendix A. Three small changes were made to the component geometry to aid in the manufacturing process. First, in order for the component to fit in the build chamber at the best print orientation (which required no supporting structures and produced the best surface finish), the flange diameter was reduced from 125 to 117.4 mm. Second, 0.4 mm of material was added to the bottom of the part (where attached to the build platform) and subsequently was removed during the wire cutting procedure that separated the built component from platform. Finally, the four small holes going through the part were replaced by small conical indentations meant to help in drill alignment for creation of the

holes. While it is possible to print the holes directly without supports, dross formation on the upper surface of the hole would still require some drilling to remove excess material on the rough upper surface. The accuracy and surface quality of the final hole as proposed is likely to be better and requires no additional machining. These small changes and the component position on the build platform are shown in Figure 34.

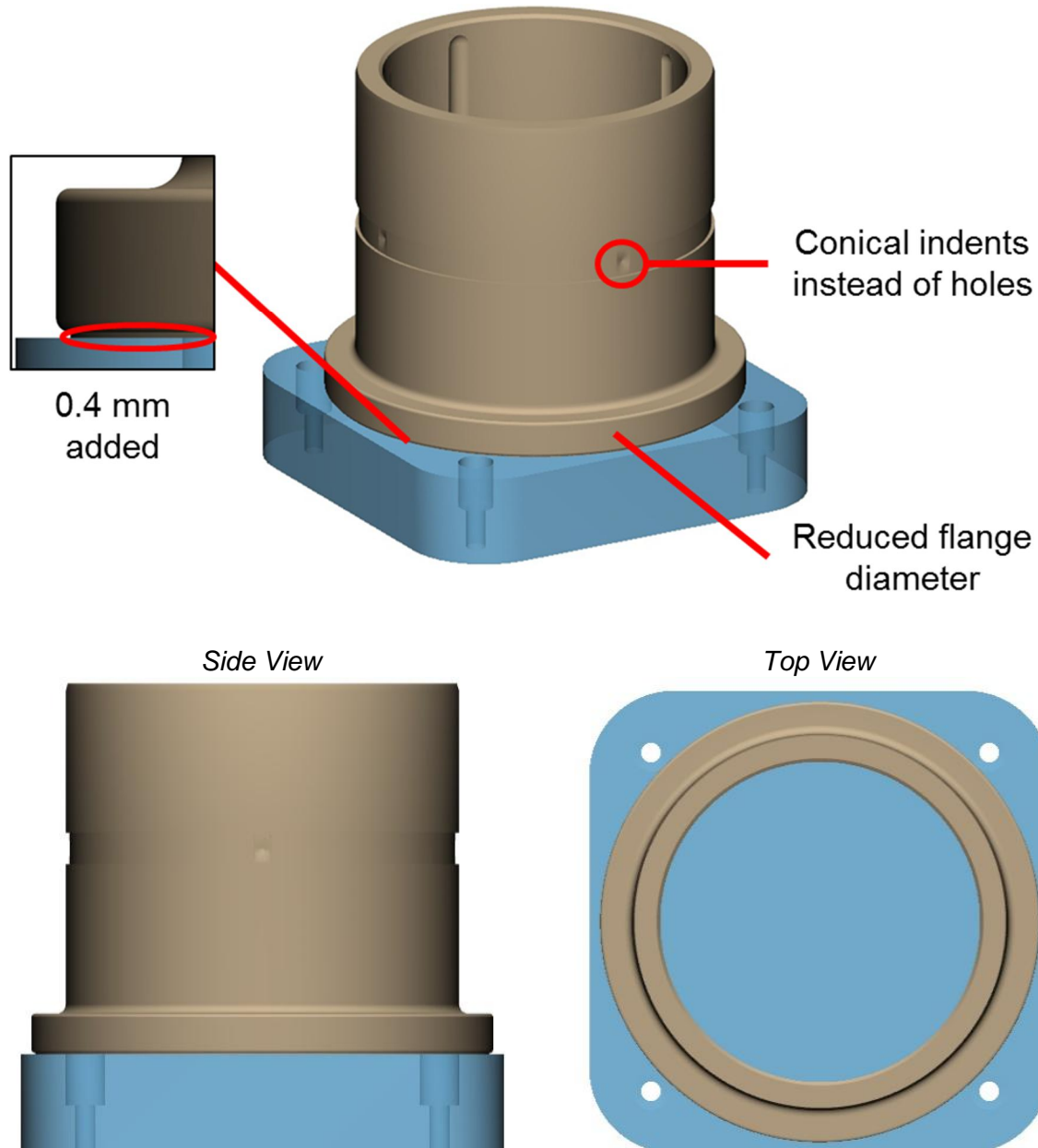


Figure 34. Changes made to part geometry (top image) and component prepared for printing (bottom).

Result

Images of the printed bushing bearing can be found in Figure 35. There was a problem during printing that the amount of powder usage was not estimated properly and the machine ran out of powder twice during the build. This meant that while the part was printed successfully, there are two small visible lines on the surface of the part where the print stopped/started.

A FARO laser scanner was used to estimate the geometric accuracy of the as-built bushing bearing. The measurement system has a reported accuracy of ± 0.1 mm. A color map showing the deviation of the component surface compared to the CAD geometry of the part is in Figure 36 with the maximum color values of red and blue indicating distortion of up to ± 0.5 mm. The highest distortion values measured were unsurprisingly due to the two print stoppages but were still well below 0.5 mm. A majority of the part has measured distortions of ± 0.1 mm or less.

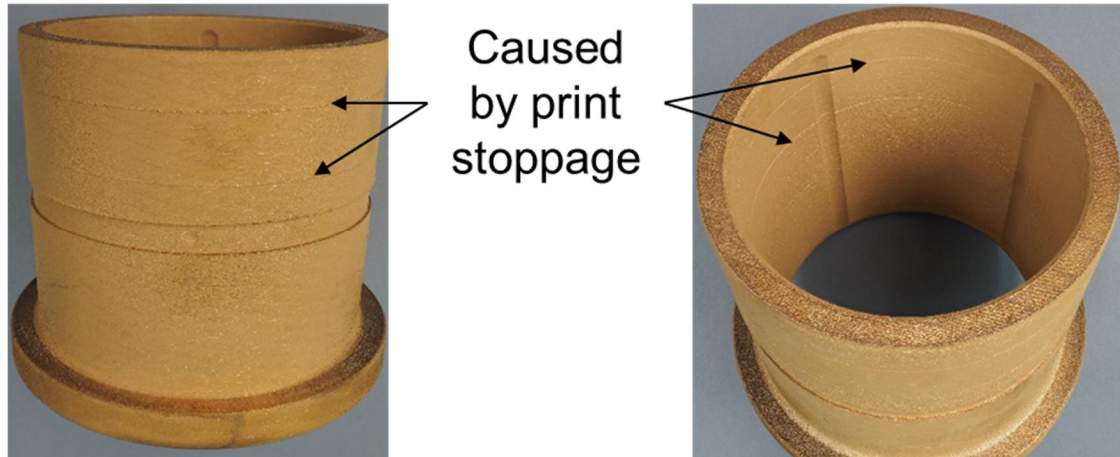


Figure 35. Photos of printed bushing bearing in CuSn10; lines seen on the component surface were caused by two print stoppages that were due to running out of powder.

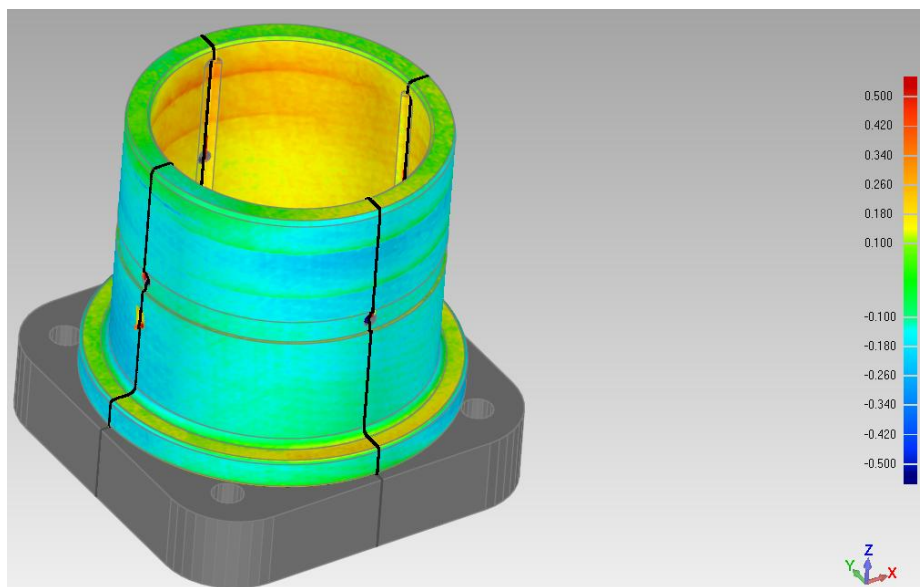


Figure 36. Results of FARO geometric accuracy measurement of bushing bearing component, with color scale showing -0.5 mm (blue) to +0.5 mm (red).

5. DACM model development for additive manufacturing

This chapter aims at introducing the Dimensional Analysis Conceptual Modeling (DACM) Framework as the modeling approach for Additive Manufacturing (AM) through a brief explanation of the theoretical backgrounds. In short the DACM Framework could be used as a tool in the manufacturing industry to optimize the output of a selected AM technology.

Later in this chapter, the possible use cases of the framework are exemplified through some case studies in additive manufacturing. This case studies, texts and figures are derived from the publications and dissertation of the doctoral student working on the HYBRAM project. Interested readers are invited to get detailed information about DACM Framework and case studies from the published articles in the field (Coatanéa, Roca, Mokhtarian, Mokammel, & Ikkala, 2016; Mokhtarian et al., 2016, 2018; Mokhtarian, Coatanéa, & Paris, 2017).

5.1 DACM Framework modeling steps and associated theories

Dimensional Analysis Conceptual Modeling (DACM) Framework provides an approach to integrate theories and methodologies related to engineering design, modeling, and simulation. The Framework offers a systematic modeling procedure to establish the causality among the variables describing the behavior of a system. It enables model integration and providing capabilities to the qualitative and quantitative simulation of the integrated models. Modeling through DACM follows a sequence of steps allowing a modeler to model a system (i.e. an additive manufacturing process), systematically. Figure 37 visualizes the sequence of steps in DACM and the theories integrated into the Framework.

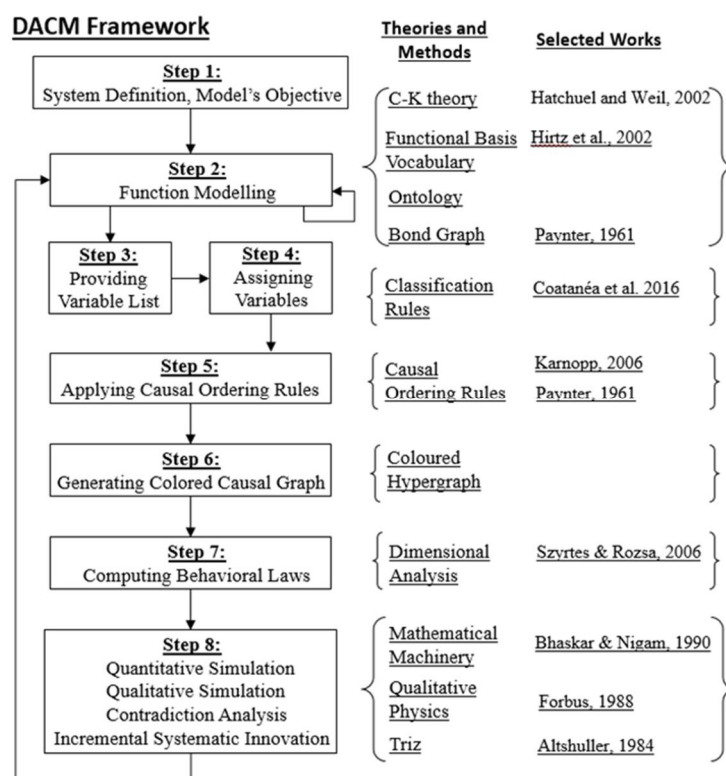


Figure 37. Modeling steps in DACM Framework. (Mokhtarian et al., 2017)

The modeling starts with a precise definition of the system's border and model's objectives. Function modeling represents the sequence of functions taking place in the Systems-of-Interest (Sol). This step is followed by the variable assignment to the functional model. Applying DACM's causal rules and color patterns lead to extract the colored causal graph among the system's variables. In the next step, dimensional analysis is applied to the causal

graph to form the system's behavioral equations. The primary result of this modeling is a colored hypergraph and a list of governing equations. This model is used further for qualitative or quantitative simulations and contradictions detection.

5.2 Function Modeling & Variable Assignment

Function modeling is a crucial step in the DACM Framework, since the ultimate system's causal graph and consequently, the final analysis is heavily dependent on the produced functional model. The function modeling in the Framework is followed by variable assignment to function model. This step requires iterative attempts to reach adequate functional architecture with the desired level of detail. The starting point can be either an existing system (a specific Additive Manufacturing process) or a combination of the Additive Manufacturing process and the part design. The overall functionality of the system is decomposed into the sequence of functions interacting with each other. Functions are represented with verbs of actions in boxes and are connected to each other with arrows in respect of the sequence of occurrence. The approach is similar to Function Analysis System Technique (FAST) diagrams for value analysis. For instance, Figure 38 exemplifies function modeling for the Direct Energy Deposition (DED) process, where the overall functionality of 'deposit melted material' is decomposed into the sequence of functions.

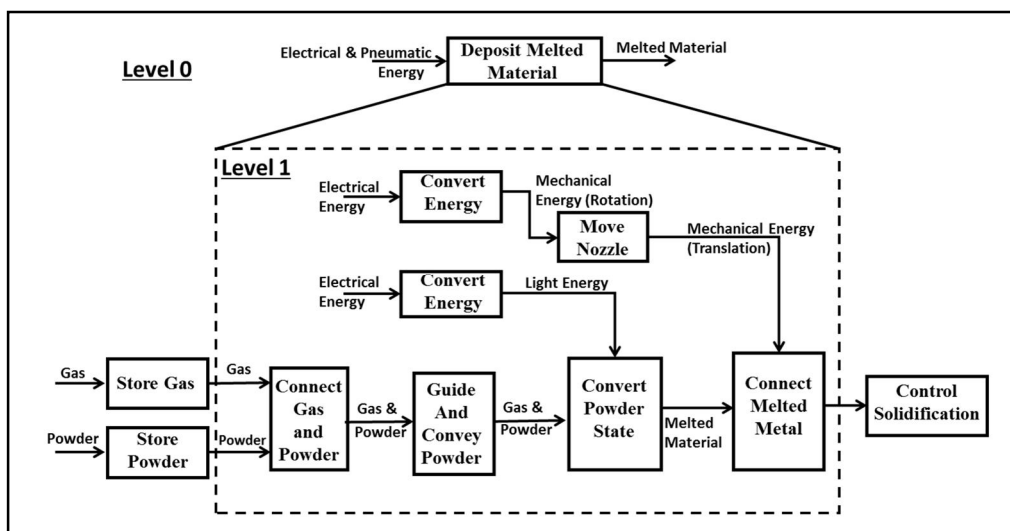


Figure 38. An example of function modeling for DED process.

The fundamental categories of variables, listed in Table 3, guide the variable assignment to the functional model. The power variables (including flow and effort) are attributed to the arrows that connect functions, and the state variables are assigned inside function boxes. Afterwards, DACM discovers the system's causal graph and behavioral laws. Note that the produced functional models using this approach, are not unique: the model's level of detail and the variable assignment in this approach depends on the modeler's reasoning. This motivates a need for the following more systematic approaches.

Table 3. Fundamental categories of variables. (Mokhtarian et al., 2017)

Primary Category of Variable	Secondary Category of Variable
Overall System variables	Energy (En) Efficiency rate (η)
Power Variables (P)	Generalized Effort (E) Generalized Effort (F)
State Variables	Generalized Displacement (D) Generalized Momentum (M) Connecting Variables (C)

DACM transforms the functional model into a ‘generic functional model’ derived from the Bond Graph (BG) theory in a systematic manner (Paynter, 1961)(Karnopp, 1979). To reduce the modeling variability and facilitate the systematic transformation of the initial functional model to the generic functional model, DACM proposes to use a limited set of functional vocabulary introduced by Hirtz (Hirtz, Stone, Mcadams, Szykman, & Wood, 2002). The reason for allocating BG elements to the functions is to take advantage of the validated causal rules in BG theory and analogy among different energy domains. Table 4 presents the mapping between function vocabularies to the nine generic functional blocks.

Table 4. Functional mapping for models transformation (to generic functions blocks). (Mokhtarian et al., 2017)

Possible name of functions to describe the organs	Functional basis vocabulary	Generic functional blocks
To transform effort into flow or flow into effort To resist effort or flow	To Magnitude	To Magnitude (Resistor: R)
To transform flow into displacement To store displacement To transform displacement into effort To provide effort	To Magnitude To Provision	To Provision (Capacitor: C)
To transform effort into momentum To store momentum To transform momentum into flow To provide flow	To Magnitude To Provision	To Provision (Inertia: I)
To transform input effort into output effort of another magnitude To transform input flow into output flow of another magnitude	To Signal To Magnitude To Convert	To Convert (Transformer: TF)
To transform input effort into output flow of another magnitude To transform input flow into output effort into output effort of another magnitude	To Convert	To Convert (Gyrator: GY)
To connect efforts of different magnitudes when flows are similar To connect flow of different magnitudes when efforts are similar	To Branch To Channel To Connect To Support	To Connect (Flow Junction: JF) (Effort Junction: JE)
To provide a constant effort To provide a constant flow	To Provision	To Provision (Source of Effort: SE) (Source of flow: SF)

The variables are assigned to the generic functional model based on the second category of Table 3. Regardless of the energy domain, the variables are classified into five generalized categories: Flow, Effort, Momentum, Displacement, and Connecting (Hirtz et al., 2002) (Coatanéa, 2005). The mathematical relationship between generic variables describes how those variables relate to each other. In each energy domain, power variable is the multiplication of effort and flow. For instance, in the electrical domain, voltage and current are equivalents of generalized effort and flow, respectively. Table 5 lists the mapping of generalized variables for several energy domains.

Table 5. Domain-specific state variables. (Mokhtarian et al., 2017)

Energy Domain	Generalized Effort	Generalized Flow	Generalized Momentum	Generalized Displacement
Electrical	Voltage (Volt)	Current (Ampere)	Flux Linkage (Volt second)	Charge (Coulomb)
Hydraulic	Pressure (Pascal)	Volumetric flow rate (m ³ /s)	Pressure Momentum (kg/m.s ²)	Volume (m ³)
Pneumatic				
Mechanical (Rotational)	Torque (Newton meter)	Angular Velocity (rad/s)	Angular Momentum (kg.m ² /s)	Angle (Radian)
Mechanical (Translational)	Force (Newton)	Linear Velocity (m/s)	Momentum (kg.m/s)	Displacement (m)
Thermal	Temperature (Kelvin)	Entropy flow rate (J/k/s)	---	Entropy (J/k)
Thermal (Pseudo-BG)	Temperature (Kelvin)	Heat flow rate (J/s)	---	Heat energy (Joule)

Displacement' is the result of the integration of the 'Flow' over time. The generalized 'Momentum' is the result of the integration of 'Effort' over time. The 'Connecting' variables cover the rest of the variables that are used to describe the material properties, geometry dimensions, etc. Figure 39 summarizes these relations, where the state variables (Momentum, Connecting, and Displacement) are located inside the elements, and the power variables are located outside the elements.

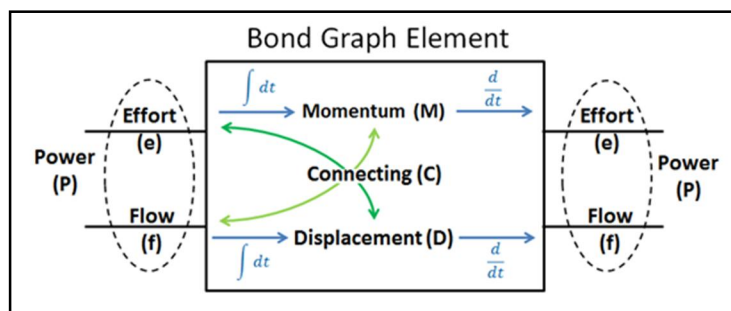


Figure 39. Representation of the generic variables and their interconnections. (Mokhtarian et al., 2017)

5.3 Causal Graph

In this step, DACM defines the cause-effect relationship among the variables in the form of a colored causal graph. DACM considers the following color pattern (four main classes), depending on the border of the model and the design nature of variables.

- Exogenous variables (Black) are outside the system border and part of the system's environment. They are imposed on the system and the designer cannot (would not) modify their values.

- Independent variables (Green) are not influenced by other variables in the system. The designer can freely modify the values.
- Dependent design variables (Blue) are influenced by other variables such as exogenous and independent variables. It is more difficult to modify and control the dependent variables.
- Performance variables (Red) are the objective variables. They usually belong to the category of dependent variables as well. They are selected by the designers to evaluate the performance of a system.

The functional architecture and assigned variables give an initial insight into the final causal graph. The simple causal rules considered for the functional models are the following. (1) The variables that appear earlier in the functional architecture are the cause of the next variable(s). (2) The exogenous and independent variables are always the cause of other variables. More generically, The cause-effect relationship is not only dependent on the sequence of functions but also on the nature of the BG element and the type of the assigned variables. An algorithm shown in Figure 40 is developed to automatize the causal graph extraction. The algorithm first verifies the one-to-one mapping between functional blocks and BG elements. Afterwards, it travels into the structure and applies the fixed causality and other associated deduced causality. The loop continues until completely covering the generic functional model (BG elements). The existence of any contradiction in this level demonstrates that the functional model is not valid or the assigned BG element is incorrect.

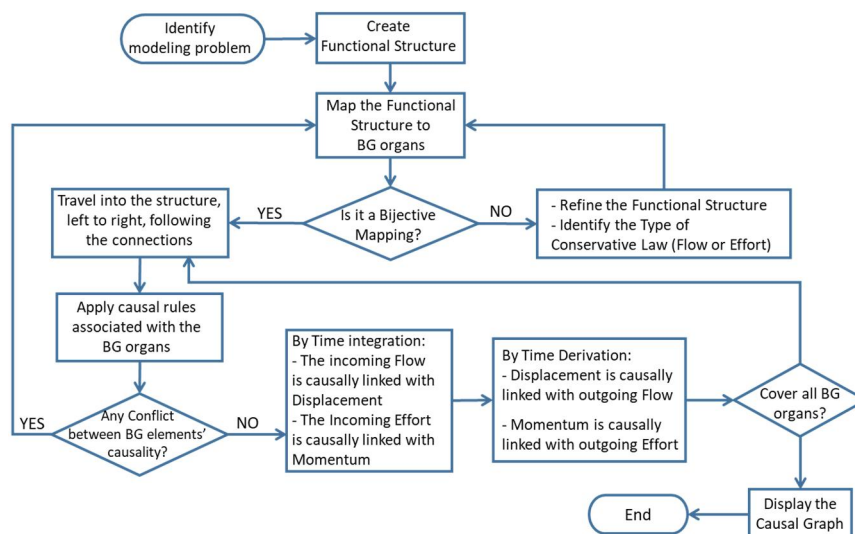


Figure 40. Description of the causal ordering algorithm. (Mokhtarian et al., 2017)

5.4 Dimensional Analysis

Dimensional Analysis (DA) in the DACM Framework seeks to deduce the mathematical relationship among variables. Initially, this step follows the causal graph and establishes the mathematical relationship among variables by applying homogeneity principals and Buckingham's π -theorem (Barenblatt, 1996). The opposite direction is pursued, in the case of enriching (building) the causal graph with existing theoretical or experimental equations. The inputs for dimensional analysis are the cause-effect relationships and the associated dimensions of variables. The algorithm depicted in Figure 41 describes the procedure of presenting dimensionless equations, in DACM Framework.

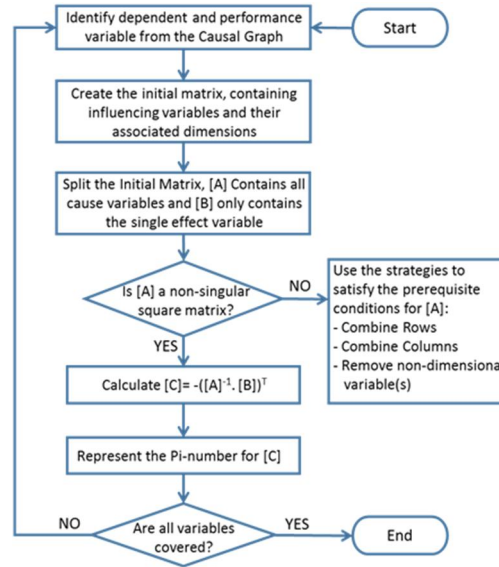


Figure 41. Description of the Behavioral Law computation algorithm. (Mokhtarian et al., 2017)

The algorithm forms a matrix for each dependent and performance variable. The matrix contains all influencing variables and their associated dimensions. The initial matrix is then separated into two sub-matrices [A] and [B] in a way that [B] only contains the variable for which we are seeking a dimensionless equation. The algorithm proceeds to calculate and represent the dimensionless equation, so-called π -number equation, if [A] is a non-singular square matrix. The algorithm computes the exponent of the dimensionless number, using following simple formula, where [C] is a vector matrix representing the exponents of variables in [B].

$$[C] = -([A]^{-1} \cdot [B])^T \quad (1)$$

The example below illustrates the construction of behavioral law from the causal graph. Figure 42 shows the extracted causal graph from a given partial functional model. The functional architecture models the material input in DED process, where the associated variables are: material providing pressure (Pr), material density (ρ), Nozzle diameter (N_d), and material mass flow rate (m). The causal graph depicts the causes and effect variables that are reformulated in (2).

$$m = f(Pr, \rho, N_d) \quad (2)$$

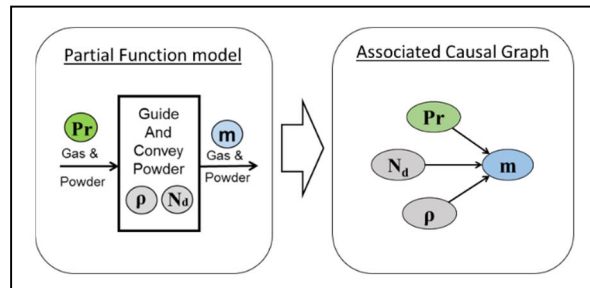


Figure 42. An example of the functional model (Left) and its associated causal graph (Right).

Table 6 shows the matrices [A] and [B] that contain all influencing variables and their associated dimensions for the variable (m). The target variable fills [B] and all other cause variables from [A].

Table 6. Matrices [A] and [B] for the variable (m) derived from the causal graph in Figure 42.

	[B]	[A]		
	m	Pr	N _d	ρ
Mass	1	1	0	1
Length	0	-1	1	-3
Time	-1	-2	0	0

In this case, [A] is a non-singular square matrix, so the calculation of [C] reveals the exponents of influencing variables for creating a dimensionless product. Equation (4) is the dimensionless number for the variable (m).

$$[C] = -([A]^{-1} \cdot [B])^T = -\left(\begin{bmatrix} 1 & 0 & 1 \\ -1 & 1 & -3 \\ -2 & 0 & 0 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}\right)^T = [-0.5 \quad -2 \quad -0.5] \quad (3)$$

$$\pi_m = m \cdot Pr^{-0.5} \cdot \rho^{-2} \cdot N_d^{-0.5} \quad (4)$$

It is possible to enrich the model with the existing experimental equations in DACM. Nevertheless, the empirical equations for fitting the experimental results often seem to be non-homogenous. Figure 43 illustrates the algorithm for re-writing these equations to be dimensionally homogeneous.

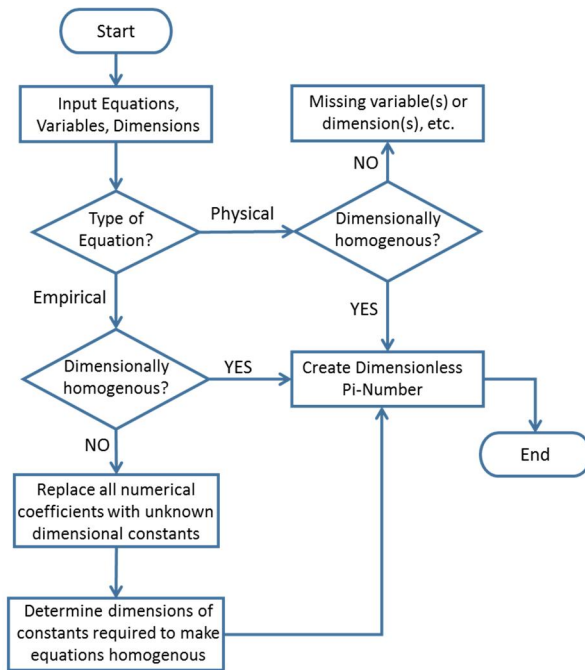


Figure 43. Description of the algorithm for equation integration (Mokhtarian et al., 2017)

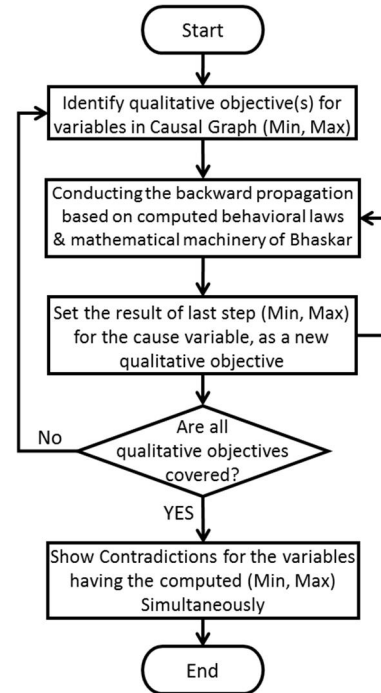


Figure 44. Contradiction detection algorithm (Mokhtarian et al., 2017)

5.5 Qualitative Simulation

Once the causal graph is established and associated behavioral laws are extracted, DACM enables the qualitative simulation using mathematical machinery. This qualitative simulation is called backward propagation. The machinery obtains the sign of the partial derivative of y_i concerning x_{ij} , as follows (where y_i is the target variable and x_{ij} are influencing variable):

$$\frac{\partial y_i}{\partial x_{ij}} = -\alpha_{ij} \frac{y_i}{x_{ij}} \quad (5)$$

The objective of qualitative simulation can be either maximizing or minimizing the performance variable(s). A positive sign in the partial derivative indicates that the variable considered in the partial derivative varies in the same direction as the variable considered in the objective. Otherwise, in the case of a negative sign, the variable varies in the opposite direction. It is possible to apply the backward propagation principle to more than one performance variables simultaneously (Multi-objective qualitative simulation).

The backward propagation of the system's objective(s) in the causal graph, the contradictions and weaknesses of the system appear. The contradictions are detected when one or more variables need to be maximized and minimized at the same time to fulfill the system objective(s). Figure 44 shows the contradiction detection algorithm from the qualitative simulation.

6. DACM Use Cases in Additive Manufacturing

This section aims at exemplifying some of the use cases of DACM Framework in AM. This report briefly oversees the case studies conducted as a proof of concept on the various application of DACM contributing the additive manufacturing sector.

6.1 Integrated design & Design for Additive Manufacturing (DFAM)

DACM enhances DFAM by presenting an approach to concurrently consider the AM machine and part to be manufactured in an integrated model. Traditionally, the design process starts with an initial set of requirement or the part geometry to be additively manufactured. Designers anticipate the AM process selection by mapping the capabilities and limitations of the AM processes with the requirements. Designers are supposed to provide the design of the part and specifications (often suitable for specific AM process), using DFAM (or in larger context DFM) principles. At this stage, designers might benefit from the existing DFAM rules, topological optimization or other principles such as part consolidation. Eventually, the more designers anticipate manufacturing challenges and refine the design to address them, the better the design is. The design provided at this stage is not necessarily the best to fulfill the requirements and designers need the feedback of the final manufactured part. The manufacturing of the designed part evolves with a different type of activities such as process parameter settings, support structure consideration and path planning for DED processes. The phase of process parameter setting is often an iterative process based on the part initial inspection. The additively manufactured part follows the rest of the manufacturing chain to post-processing and heat treatment if needed. Once the manufacturing process is completed, various tests and measurements evaluate the part against the requirements. It is at this stage that designers get feedback on the initial provided design, which is quite late in the design and manufacturing phase. Due to the part validation process, the designer can extract the DFAM rules and consequently tailor the part design and manufactures tailor the process settings. DACM enhances DFAM by providing an approach for concurrent consideration of AM process and the part, and for anticipation some of these feedbacks early in design stages. The DACM modeling approach is applied to Fused Modeling Deposition (FDM) process as a proof of concept to illustrate how DACM enhance DFAM. Detailed modeling steps can be found in the published paper, supported by HYBRAM project (Mokhtarian et al., 2018). At the stage, a causal graph integrating the FDM process and the model of the part design is extracted using the DACM modeling approach.

Figure 45 illustrates the causal graph of the FDM process. The volumetric flow rate (\dot{Q}_6) and the temperature (T_{output}) of extruded material are considered as performance variables. Those variables have a significant impact on dimensional accuracy, bonding quality, and the final mechanical properties of the part produced by the process. A simple rectangular geometry has been considered as a test part. The key characteristics of the desired part are the specified flatness tolerance (tv), relatively small radius in the corners (R) and uniform bonding quality between layers. The geometrical flatness tolerance is affected by the variation in material deposited per length ($\Delta(M/L)$). The travel velocity of the nozzle and melted material flow rate are the causes of the amount of material deposited per length. The bonding quality, also known as coalescence, plays an essential role in the part's final mechanical properties. One of the key variables in determining the bonding quality is the temperature of the fused filament (Sun, Rizvi, Bellehumeur, & Gu, 2013); minimizing the variation in the temperature of the fused filament supports uniform bonding quality on the part. Figure 45 represents the partial causal graph of the integrated model (FDM process and the part to be manufactured). The performance variables are shown in red and the qualitative objectives are underlined with different colors. The results of the backward propagations of the qualitative objectives and the two contradictions discovered are shown in Figure 45 (Mokhtarian et al., 2018). Detection of the contradictions at the early stages of design guides the designer toward the most valuable and required part design and process improvements.

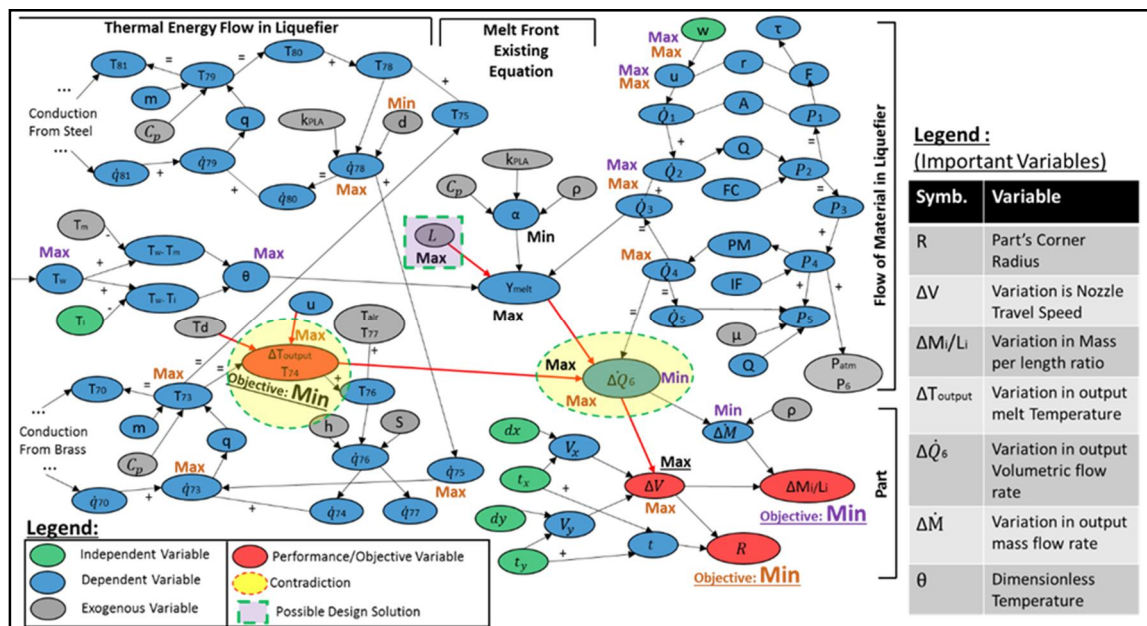


Figure 45. Partial causal graph of FDM liquefier and the part to be manufactured. (Qualitative objectives are underlined. The backward propagations on the graph are shown with the same colors). (Mokhtarian et al., 2018)

To evaluate this qualitative analysis shown in Figure 45, we have considered a printing test part. Excluding the starting point, the test part has two round corners ($R_1=1\text{mm}$ and $R_2=2\text{mm}$) and a sharp corner. The geometry of the test part is shown in Figure 46. The initial printed parts demonstrate the predicted defects around corners and poor bonding quality near the starting point (see Figure 46).

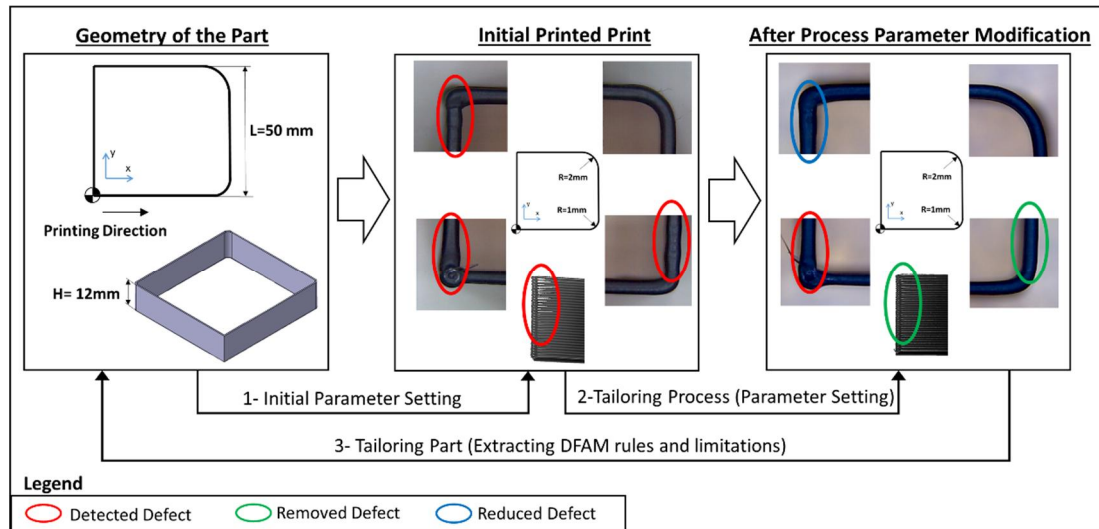


Figure 46. Printing result before and after process parameter modification. (Mokhtarian et al., 2018)

The defects appeared around all the corners except the corner with the two-millimetres radius. The contradictions found in the causal graph demonstrate that acting on the variation of polymer volumetric flow rate in the nozzle outlet ($\Delta\dot{Q}_6$) can remove or reduce the defect. Variable ($\Delta\dot{Q}_6$) is the difference of volumetric flow rate before and after the radius. Nevertheless, volumetric flow rate (\dot{Q}) is a dependent variable. The slicer software (here Repetier) calculates the filament feed rate (u) and consequently volumetric flow rate (\dot{Q}) according to the input value of nozzle travel speed (V). On the other hand, the inspection of the initial printed part illustrates that the excess of deposited material after the radius causes the defect (Figure 46). Therefore, we have reduced the filament flow rate in the G-code generated by the slicer. Furthermore, by adjusting temperature, the defect around the corner with $R=1\text{mm}$ is removed and improve the bonding quality near the starting point (tailoring process settings). In the sharp corner's zone, the defect was reduced, but never removed. Moreover, the minimum achievable radius was 0.6 mm. This limitation led to a DFAM rule for existing machine setup. Therefore, the part design should be modified and consider a corner radius superior to 0.6 mm (tailoring part design). This is the limitation induced by the available FDM machine design and can be improved by the redesign of the machine (tailoring AM machine). The concurrent consideration of the part and process models in DACM anticipated the system's weaknesses for fulfilling design requirements at the early design stages and proposed several feasible solutions. The experimental tests verify those weaknesses and propose redesigning the part (considering $R>0.6\text{ mm}$).

6.2 Exploring design space using Bayesian Network

From the other side of spectrum, DACM provides a model of interactions and dependencies between the variables, which describes the phenomena of a system (manufacturing process). Each of these variables has a domain in which they can take values. Therefore, domain space to explore is a space with a dimension equal to the number of independent variables. This means that an increase in the number of independent variables and their associated domain interval lead to increase the complexity of the space to explore. In the design phase, this domain should be explored to find a suitable combination of variables for the system under design. On the other hand, designers may have preferences and consideration for choosing the values for the independent variables. These preferences may be coming from the experts' knowledge in that domain, which is hard to model, or the designer may simply have some consideration that is not included in the model. Therefore, some

values in the domain of each variables can have a bigger chance to be chosen over the other values.

A Bayesian network is a probabilistic model, which can show a combination of qualitative and quantitative aspects of a system in a single model. The qualitative part is a directed acyclic graph (DAG) that depicts dependency and independency relations between variables of the system. In a DAG, variables of the system are shown with nodes, and the dependencies between them are shown with a directed link. A DAG in the Bayesian network can be considered as a causal network under certain circumstances. The quantitative part has two aspects. If the variables are continued variables, the numerical values or probability distribution of them are associated with each node. If the variables are categorical, intervals or discrete, the states of them are associated with the nodes. The other aspect of the quantitative part is the local conditional probability tables related to each variable, which is a factorization of the joint probability distribution of the variables in the system. For example, for categorical or interval variables, The local conditional probability tables (CPT) show the probability of occurrence of each of the variables states, based of occurrence of each of the states of their parent nodes.

Bayesian networks can handle both the design space and the probabilities behind the choices of values for variables. The causal graph resulted from DACM framework can be used as the DAG for a Bayesian network. Independent variables' domains can be divided into several intervals, and the preference of designers can be modeled as probability tables for each interval in Bayesian networks. The preference of designers for independent variables' intervals can be collected through a probability assessment process, for example, the Analytical Hierarchy Process (AHP). The mathematical equations and Pi number equations used in DACM can be used to find the CPTs for the dependent variables and performance variables.

After creating and validating the model, the model can be used for both prognosis and diagnosis. In prognosis, the probability that a performance variable takes the values in its intervals can be calculated based on the intervals of values chosen for the independent variables. This can be used to predict the possible effect of choosing a specific value interval for independent variables of the performance variables. Because the probabilities of independent variables are based on the expert knowledge, the model can also help the designers to know what are the most relevant values to choose for the variables. In diagnosis, for a specific interval in performance variable, the probability of all intervals of the independent variables can be inferred. This can be used when a designer needs to choose the correct combination of variables, in order to have the performance variables in a specific interval.

This approach explained above is applied to an additive manufacturing case study. This case study aims at exploring the design space to and study the probabilities of reducing or removing the curling defect in Powder Bed Fusion (PBF) technologies. The Curling defect is one of the recurring defects in metal AM. It occurs in the areas of the parts that are not supported by material: 'overhang surfaces'. The excessive heat energy input (overheating) leads to a cumulative thermal constraint on the part being processed. The cumulative thermal constraint finally results in the deflection of the overhang surfaces upward. The support structure is used for two main reasons: to dissipate excessive heat and to resist distortion by increasing the inertia of the part. Design and manufacturing strategies generate contradictory effects; for instance, applying a more dense support structure to minimize the curling effect increases the manufacturing time, material cost and difficulties involved in removing the supports. The design space in the functional model shown in Figure 47 is divided into three domains: cyclic functions of the AM process, useful functions of the support structure and non-desired functions.

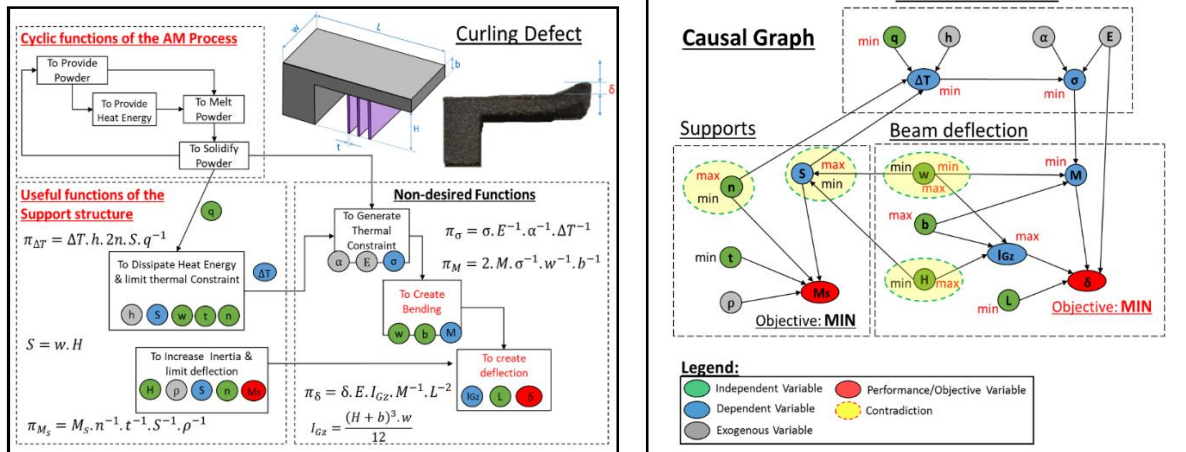


Figure 47. Left: Functional model for curling defect modeling, Right: Causal Graph for Curling Defect. (Mokhtarian et al., 2018)

The causal graph shown in Figure 47, is transformed to the Bayesian network simulation environment, based on approach mentioned above. Figure 48 illustrates the Bayesian network simulation environment for the study of the curling defect. The model can answer the questions such as ‘what if we impose to the curling defect to be between 0 entre 0.01 mm (evidence 1) and if simultaneously we impose that the surface of heat exchange will remain in the low range (evidence 2). Those evidence are forcing probability values for the specified nodes (see red arrows in the Figure 48). This is immediately propagated in the graph and it is affecting the other probabilities (grey arrows on each of the blue bars in the probability charts). We extract from the inference on the model that we have a probability of 79.09% to keep the height of the beam to be in the range 6 to 12 mm and 67.57% to have the length of the beam to stay in the range 15 mm to 25 mm. Similarly, it tells us that it might be good to modify the coefficient of convection to average (50,15%), perhaps leading to a forced convection to cool the layers. Similarly, it tells us that we have to keep the total of support low. This approach is powerful and can be used early to select optimal value ranges of design and manufacturing parameters. This model can also be used to evaluate the impact of design and manufacturing choices early in the development process.

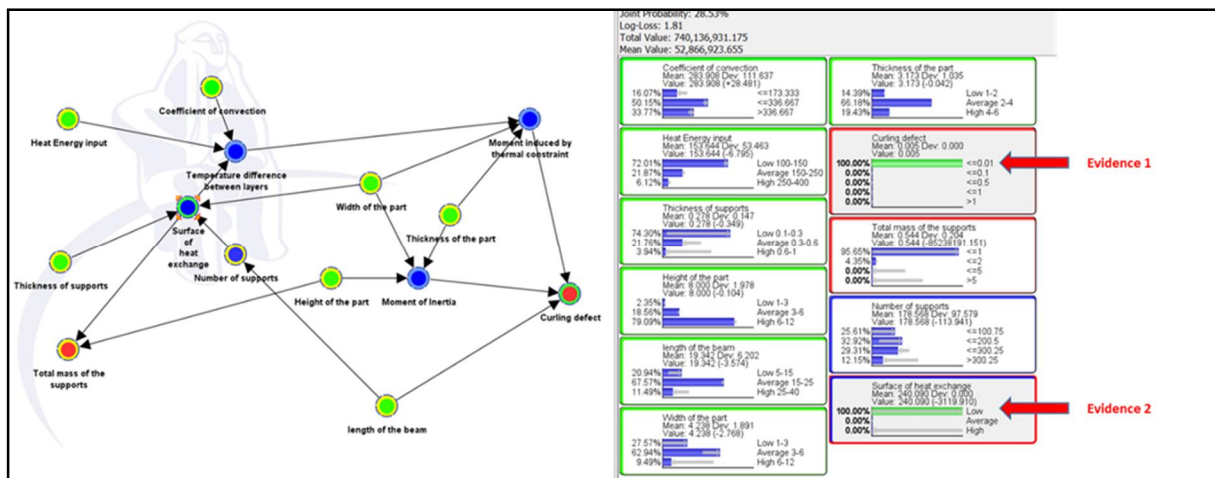


Figure 48. Bayesian network simulation environment for the curling defect of a beam manufactured using the Powder Bed Fusion technology.

6.3 Metamodeling enabling Machine learning Techniques

Another approach to enable quantitative simulation for the models developed by DACM is to link models to Artificial Neural Network. This approach shows great potential in AM in terms of the reusability of the model and capturing pre-existing validated knowledge/models.

Artificial Neural Networks (ANN) as a modeling strategy has been widely used to approximate complex functions. In this context, ANNs can be considered as one type of metamodeling approach. The main challenge in the application of ANN is the need for a large number of training data. Moreover, ANN faces the central issues of reusability and interpretability. The results of ANNs are case-specific and difficult to interpret (Nagarajan H., Mokhtarian H., Jafarian H., Coatanéa E., Wang G., Wu D. Tsarkov V., 2018).

To enhance the reusability and interpretability in ANN, DACM Framework suggests developing a modular knowledge-based Artificial Neural Networks (KB-ANN) topology based on the established causal graph model. In this approach, the causal graph of the whole system is broken down into multiple small ANNs. Each small ANN is dedicated to characterize a functionality in the system or a physical phenomenon that takes place in the AM process. This (KB-ANN) topology, is a hybrid topology of ANNs that combines the topological zones derived from knowledge of the system (AM process) and other zones where the missing knowledge is modeled using classical ANNs. The advantages of the proposed approach fall into three main points (not limited to) (Nagarajan H., Mokhtarian H., Jafarian H., Coatanéa E., Wang G., Wu D. Tsarkov V., 2018).

- 1) **Interpretability:** The major advantage of this approach comparing to classical ANN is the integration the pre-existing knowledge on the system (AM process) and eventually changing a black box model to a gray box model for better interpretability. Encoding Knowledge in KB-ANN can enable superior interpretation capability to the model.
- 2) **Reusability:** the small ANNs in hybrid architecture in KB-ANN describe the physical phenomenon, laboratory experiments results can be used to model different machines and processes in case of having common physical phenomenon taking place in those processes, and eventually enhance the reusability of developed models and data.
- 3) **Experimentation:** the proposed approach relies partially on experiments. The experimental datasets are not used to train the entire model but to train only the zones of the model that the knowledge does not exist in the form of deterministic or empirical equations.

The DACM framework provides the approach mentioned above to integrate different models, including experimental and theoretical models. It represents models in the form of the combination of the causal graph governing equations. The pre-existing knowledge integrated into the models can be either deterministic equations, empirical equations. The available deterministic and empirical equations encode the pre-existing knowledge zone. The input and output variables are extracted from the causal graph to model the zones where the missing knowledge is required using classical ANNs. Developing such modular ANN topology is not unique. The level of detail of the KB-ANN depends on the level of detail in the causal graph, availability of datasets, and the availability of the sensors to measure parameters on the machine. The proposed approach also offers an indication about the variables that need to be monitored in the system or process under investigation. Figure 49 illustrates a KB-ANN modular topology for the FDM process based on the causal graph developed in the section above. This hybrid ANN topology contains some selective sequence of functions and phenomena taking place in the FDM process. In order to be able to train the small ANNs in the current topology of KB-ANN shown in Figure 49, training datasets are required for the red and blue variables. The training values should be gathered using either

measurements, sensors, and simulation results. Hence, the causal graph indicates the zones (variables) that need to be monitored or measured in the system. One can simplify the causal graph or slightly change the logic of the causal graph according to the availability of monitor and measurement devices.

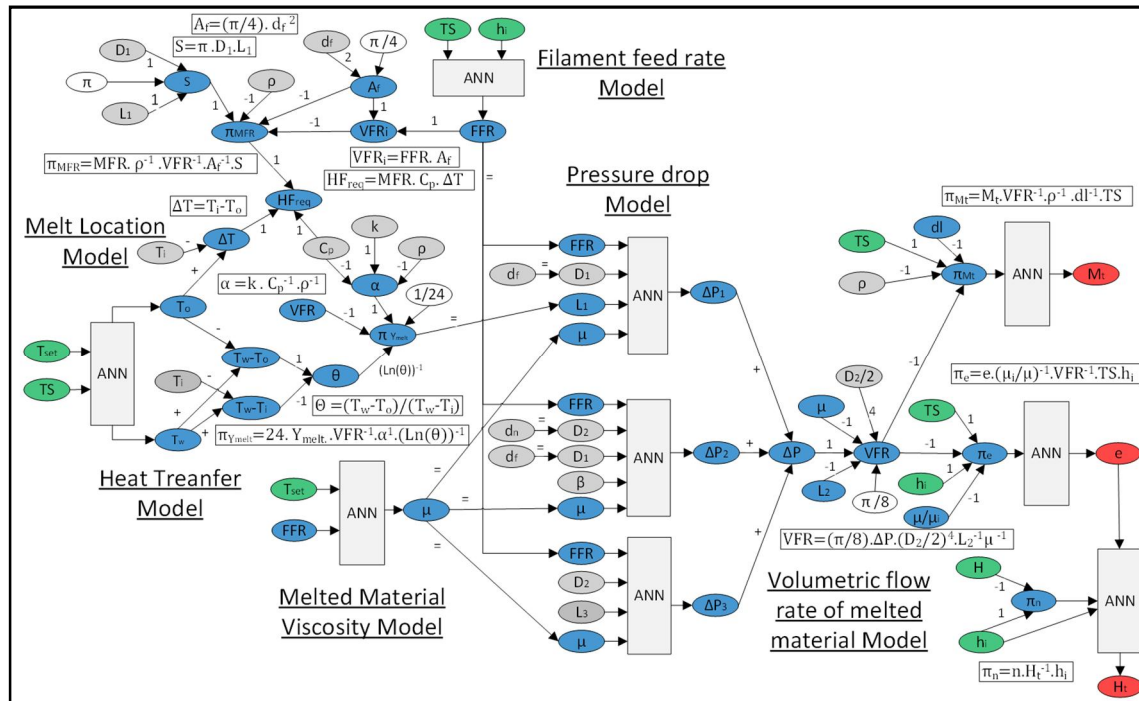


Figure 49. A modular KB-ANN topology for the FDM process using causal graph developed by DACM Framework.

7. Short abstracts of industrial projects

Fastems Oy Ab

Fastems' had two upper level goals in Hybram project. Firstly, our target was to gather knowledge about the trends and maturity level of additive and hybrid manufacturing technology of metal parts. Secondly, we wanted to research how AM resources could be integrated into industrial manufacturing and Flexible Manufacturing Systems (FMS) as well as how is it different compared to integrating conventional subtractive manufacturing technology like machining centers.

There is a clear trend that industrial manufacturing is moving towards smaller lot sizes and more customized products, which need new level of flexibility from manufacturing technologies. Ultimately many manufacturer's goal is to get closer to economically feasible lot-size-one production. Alongside its unique benefits, AM can be a key factor in this development and thus manufacturing players across the globe are already heavily investing in R&D to investigate its possibilities. There are already examples of industrial applications for parts made with metal AM. These parts are used in jet engines, gas turbines and supercars as well as in medical industry in for example dental parts or different kind of implants.

AM itself is tool-less manufacturing, but currently it is not enough for manufacturing ready-to-assemble or -use parts. AM is part of the process chain, which includes also different quality assurance, heat treatment as well as subtractive process phases. This fact opens up novel business opportunities for integrators.

- Depending on the printed part's pre- and post-processing needs, the actual printing can be just a small part of the process. Regarding a questionnaire made by Wohlers Associates to metal AM service providers, printing takes in average 54,1 % of the time, but with some geometry this can obviously be a much lower portion.
- AM is currently a highly manual process. While developing the materials and printing process itself, AM machine providers have not made much effort to ease integration. This is now changing, and many machine providers are partnering with large manufacturers in different industries to develop the industrialization of the technology.
- Powder bed fusion is currently the most widely used AM technology in metal manufacturing industry and it is already a robust and mature enough technology for many industrial applications. Still, automated quality assurance made with in-process monitoring and post-process measurements needs to get to a different level to automatize production of critical parts.
- To unpack a printed part and make a setup for a new print can take for example two to three hours. It is becoming more common that instead of doing powder removal in a build chamber, the AM machine manufacturers are designing the machines so that the build chambers can be removed from the machine after the print process and transferred to separate powder removal stations where an operator does the powder removal. This enables a new print process to be started after the previous one has been printed.
- In many cases when creating a new part, hybrid manufacturing systems instead of hybrid machines could be the right choice. These systems would include separate AM machines and separate machining centers and for example robotized finishing cells. A high-level information system (e.g. Fastems' MMS) would optimize the production flow and put the machine downtimes to minimum.

Integrating of AM resources to a manufacturing system includes fitting of hardware, software and electrical interfaces between the machines and the system. The principle is the same than with conventional machines, but it is a new kind of a task in many ways, especially in the hardware side. In the first stage it could be that a human operator does some of the stages like powder, support structure and part removal from the build plate manually. An AM machine integrated to an FMS would automatically change its build chamber after a finished print job internally or with a similar Automatic Pallet Changer (APC) that is in use today with conventional machining centers. The FMS could move the build chamber to an isolated production cell with a powder removal station, where a human operator removes all excess powder. There could be then a robot arm which move the build plate to heat treatment, machining centers and part removal from the build plate. Again, these could also be centralized to different manufacturing cells and the stacker crane or robot of the FMS could handle the build chambers or plates.

Because the geometry of printed parts can vary drastically, methods to handle parts of any geometry should be developed. Build plates could have attachment points so they could be handled by robots. If individual printed workpieces need to be handled by robots, they could have standard features for gripping either designed to the part's geometry itself or in the support structure. On the on hand, there are problems to find suitable fixtures which can withstand heat treatment's high temperatures.

Like in automatization of manufacturing in general, integration of AM can significantly reduce manufacturing duration and downtimes and improve the quality and success rate of printed products by reducing and eventually preventing human errors. In addition, an important benefit is the improvement of human safety. Metal powder can be dangerous because of its flammability and other bad health effects caused by breathing or otherwise getting in contact with the material. This is one of the key drivers for the AM machine manufacturers to look into integration.

Sandvik Mining and Rock Technology

Sandvik role in collaborative research was to concentrate design and post processing of parts while research members of the consortium focused the core of printing. Sandvik aim was to fill hybrid machine (AM+Machining) gap in Finnish industry, but technology was not ready to industrial solutions.

During the research, many hype driven expectation met the real life and fell apart. Sandvik brought to research consortium deep knowledge of metal printing practice collaborating Sandvik Additive Manufacturing Center in Sweden and Sandvik Osprey in Great Britain the producer of metal powder. There the limitations and potential success were tested by several pieces. The biggest conclusion from the survey was that design thinking is the core and all solutions made from basic forms for instance round and square blanks, were not typically profitable solutions for AM. In rock drill power concept development one path to AM was found by changing paradigm of design thinking, but at the end more conventional solution was found. The metal AM manufacturing concept requires effective safety procedures that are tested in Sandvik AM Center. When knowing their approach in full scale industrial production, safety issues raise questions for those companies who have integrated AM in their standard production premises. There are potential to companies like Fastems for automatic handling and safety systems development.

When studying deeper post processing that is needed with AM blanks, too. Often in machine design tolerances, surface roughness and material properties are needed. Nearly in all cases AM method needs post processing (i.e. machining and heat treatment). So potentially AM (metal printing) is one manufacturing method among the others. Several material studies were carried to investigate the potential needs to AM resulting conclusions of weak basis of understanding the microstructure. This observation obviously leads to need for further research to standardize AM one of the manufacturing methods.

Several tests were carried out with VTT to anchor knowledge to test pieces even though the gap to conventional manufacturing methods was big. In design knowledge, the developed design tools and design competence was tested with Enmac (one of the members in Hybram consortium). AM-design software's are obviously developed mainly to save expensive metal powder and leading structural optimization stress and strength as driver. This path does not support thinking where design freedom should be the driver.

Post processing studies lead to conclusions that 5-axis machining centers are supporting well several shapes that AM method potentially requires. Same time the combination of new casting methods, forging and modern digital machining centers with smart tools with sensors will narrow the space of AM method.

However, low volume and small sized pieces combination with novel complex design solutions could create potential for metal printing. It was clear conclusion that a lot of development will be needed before the promises of hype can be reached. There is a niche segment for AM driven by design solutions.

Sandvik strategy with AM in high value industrial products is to outsource potential pilot solutions and follow up Sandvik Additive Manufacturing Center progress and learning. AM with metal powder could be used in complex machining tools and helping complex and fast prototype manufacturing.

Sandvik needs for further research among metal based AM would be in integration of sensors to metal surfaces. Knowing that it is categorized nearly impossible, we just hope that there will come a researcher who do not know that. Research focus should be expanded to non-metal solutions, too.

Pasi Julkunen, Head of Technology, Rock Drills, Sandvik Mining and Rock Technologies

PTH-Metalli Oy

PTH-Metalli's main objectives in participating in the HYBRAM research project were twofold. Firstly, PTH wanted to learn AM production technology and 3D metal printing methods from the supplier perspective i.e. investigate possibilities and develop capabilities for any customer demand in near future. Secondly, PTH wanted to learn "hybrid additive manufacturing", where parts are mainly manufactured with conventional methods, but some specific details will be added with AM technology.

To meet the first target, PTH actively promoted 3D printing awareness amongst customers. Due to the role of OEM parts manufacturer, all parts must need the criteria specified in the drawings. Therefore, PTH cannot use 3D metal printing as a production method for parts that are meant to be produced conventionally. Very soon it was obvious that any AM produced part need specific design for 3D printing. Unfortunately, no commercially designed parts for 3D printing were needed during the research project.

Hybrid additive method would be beneficial for some parts made in conventional way. E.g. batch code would be easily added in final production phase. Equally useful are control markings printed at an accurate distance so that one can measure if there is any metal fatigue over time. Metal fatigue is critical in all parts subject to high dynamic forces such as harvester booms or other lifting equipment. Fortunately, PTH had invested in a 13-axis robotized welding system with optional CMT system. With basic welding adjustments it was possible to add markings such as batch codes, letters and numbers, bars, arrows etc. on conventionally produced parts. Even though this method differs from the Powder Bed Fusion and Direct Energy Deposition methods, it has proven to be an easy add-on in current production.

PTH-Metalli Oy is a full-service OEM workshop manufacturing and supplying parts for assembly lines, new product development and spare parts for the aftermarket. As an OEM parts manufacturer and supplier, the purpose of business is to produce parts according to customer drawings and specifications.

Enmac Oy

At the beginning of HYBRAM project Enmac Oy had the objective to increase their competitiveness by reaching the status of a forerunner in redesign of AM parts by utilizing topology optimization. During the project they redesigned Sandvik's Pikehead component and showcased their ability to redesign a part to utilize the design freedom of AM.

CM-Tools Oy

The goal of CM-Tools Oy in the HYBRAM project was to survey the AM technologies and materials to assess the potential of AM in their operations. The suitable AM-technologies and machines, service concepts, business models were evaluated during the project. The potential of AM was recognized especially in the manufacturing of moulding components.

8. Conclusions and Summary

In the HYBRAM project, the key features in Additive and Hybrid manufacturing technologies were identified and analyzed, providing us the knowledge of the potential applications and the main limitations of these technologies. The metal AM technologies are developing rapidly with the attention of the machine manufacturers being in industrialization of the technologies. This is seen as improved efficiency and quality control systems in the printers. Despite the technological developments the systems are not designed with full integration capabilities in mind which poses challenges for integrating them in a factory environment. Both the hardware and software require development to reach the state where full integration is possible. The concept for AM integration is however shaping up and the cooperation of the different players i.e. the machine manufacturers, the integrators and the end users plays a crucial role in lowering the threshold for integrating AM machines as part of the manufacturing process chain. In the project the further development of a Dimensional Analysis Conceptual Modeling Framework (DACM) was carried out. The Framework offers a systematic modeling procedure that can be used to describe the behavior of a system such as an AM process.

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APPENDIX A

SLM Solutions Metal Powders

The discussion surrounding the Chapter 4 case studies included the creation of components by laser powder bed fusion techniques and utilizing various metals (SLM Solutions, 2018) describing the makeup and properties of these materials.

316L

SLM Solutions' Stainless Steel 316L is an austenitic high chromium steel with excellent processability on SLM Solutions' additive manufacturing machines. 316L is often used in applications requiring good mechanical properties and excellent corrosion resistance, especially in chloride environments.

Chemical Composition (nominal), %

Element / Material	Fe	Cr	Ni	Mo	Si	Mn	C	N	P	S	O
316L (1.4404) 10-45 µm	Bal.	16.00 - 18.00	10.00 - 14.00	2.00 - 3.00	1.00	2.00	0.030	0.10	0.045	0.030	0.10

Mechanical Data ⁵	Formula Symbol and Unit	1.4404 / 316L ^{2,3}
Tensile strength	R _m [MPa]	633 ± 28
Offset yield stress	R _{p0.2} [MPa]	519 ± 25
Break strain	A [%]	31 ± 6
Reduction of area	Z [%]	49 ± 11
E-Modul	E [GPa]	184 ± 20
Hardness by Vickers	[HV10]	209 ± 2
Surface roughness	R _a [µm]	10 ± 2
Surface roughness	R _z [µm]	50 ± 12

1 Layer thickness 30 µm
2 Layer thickness 50 µm
3 As built

4 Heat treated
5 Process conditions and parameters according to SLM Solutions standards

Material Characteristics

- Very good corrosion resistance
- High strength under elevated temperatures
- High ductility

Typical Application Areas

- Aerospace /Automotive
- Surgical Instruments
- Food Industry
- Maritime

Figure 50. Summary of SLM Solutions 316L stainless steel powder (SLM Solutions, 2018).

H13

SLM Solutions' Tool Steel 1.2344 is a chromium containing martensitic tool steel. Also known as H13, this material is used in tooling applications that require exceptional strength and toughness.

Chemical Composition (nominal), %

Element / Material	Fe	C	Cr	Mn	Mo	Ni+Cu	P	S	Si	V
H13 10-45 μm^2	Bal.	0.32 - 0.45	4.75 - 5.50	0.20 - 0.60	1.10 - 1.75	0.75	0.03	0.03	0.80 - 1.25	0.80 - 1.20

Mechanical Data ⁵	Formula Symbol and Unit	H13 ^{2,3}	H13 ^{2,4}
Tensile strength	R_m [MPa]	1525 \pm 146	1888 \pm 6
Offset yield stress	$R_{p0.2}$ [MPa]	1507	1655 \pm 23
Break strain	A [%]	3	8 \pm 1
Reduction of area	Z [%]	3	15 \pm 3
E-Modul	E [GPa]	217 \pm 19	256 \pm 38
Hardness by Vickers	[HV10]	-	-
Surface roughness	R_a [μm]	-	-
Surface roughness	R_z [μm]	-	-

1 Layer thickness 30 μm
2 Layer thickness 50 μm
3 As built

4 Heat treated
5 Process conditions and parameters according to SLM Solutions standards

Material Characteristics

- High tensile strength
- Moderate corrosion resistance
- Resistant to thermal fatigue cracking

Typical Application Areas

- Injection moulding
- Tooling

Figure 51. Summary of SLM Solutions H13 tool steel (SLM Solutions, 2018).

17-4PH

SLM Solutions' Stainless Steel 17-4PH is a martensitic precipitation-hardening stainless steel. 17-4PH is suitable for applications requiring high strength and hardness combined with moderate corrosion resistance.

Chemical Composition (nominal), %

Element / Material	Fe	Cr	Ni	Cu	Nb + Ta	Si	Mn	C	N	P	S	O
17-4 PH (1.4542) 10-45 µm	Bal.	15.00 - 17.50	3.00 - 5.00	3.00 - 5.00	0.15 - 0.45	1.00	1.00	0.07	0.10	0.04	0.03	0.10

Mechanical Data ⁵	Formula Symbol and Unit	17-4PH ^{2,3}
Tensile strength	R _m [MPa]	832 ± 87
Offset yield stress	R _{p0.2} [MPa]	572 ± 25
Break strain	A [%]	31 ± 3
Reduction of area	Z [%]	55 ± 4
E-Modul	E [GPa]	155 ± 22
Hardness by Vickers	[HV10]	221 ± 4
Surface roughness	R _a [µm]	9 ± 2
Surface roughness	R _z [µm]	54 ± 15

1 Layer thickness 30 µm
2 Layer thickness 50 µm
3 As built

4 Heat treated
5 Process conditions and parameters according to SLM Solutions standards

Material Characteristics

- Precipitation hardenable
- Excellent tensile strength
- Moderate corrosion resistance

Typical Application Areas

- Aerospace
- Medical
- Chemical / Petrochemical
- Paper / Metalworking industries

Figure 52. Summary of SLM Solutions 17-4PH martensitic precipitation-hardening stainless steel (SLM Solutions, 2018).

1.2709

SLM Solutions' Tool Steel 1.2709 is a maraging tool steel with a high content of alloyed nickel and some molybdenum. 1.2709 is suitable for many tooling and high performance applications that require high strength and toughness.

Chemical Composition (nominal), %

Element / Material	Fe	Ni	Mo	Ti	Co	Al	Mn	C	P	S
1.2709 10-45 µm	Bal.	18.00 - 19.00	4.70 - 5.20	0.50 - 0.80	8.50 - 9.50	0.05 - 0.15	0.10	0.03	0.01	0.01

Mechanical Data ⁵	Formula Symbol and Unit	1.2709 ^{2,3}	1.2709 ^{2,4}
Tensile strength	R_m [MPa]	1135 ± 29	1784 ± 313
Offset yield stress	$R_{p0.2}$ [MPa]	987 ± 15	1920 ± 12
Break strain	A [%]	11 ± 1	3 ± 1
Reduction of area	Z [%]	44 ± 2	10 ± 0
E-Modul	E [GPa]	113 ± 8	125 ± 5
Hardness by Vickers	[HV10]	373 ± 2	-
Surface roughness	R_a [µm]	9 ± 1	-
Surface roughness	R_z [µm]	67 ± 5	-

1 Layer thickness 30 µm
2 Layer thickness 50 µm
3 As built

4 Heat treated
5 Process conditions and parameters according to SLM Solutions standards

Material Characteristics

- Martensite hardenable
- High toughness
- High tensile strength
- Good properties up to ca. 400°C

Typical Application Areas

- Injection moulding
- Engineering parts
- Automotive
- Aerospace

Figure 53. Summary of SLM Solutions maraging tool steel (SLM Solutions, 2018).

CuSn10

SLM Solutions' Bronze CuSn10 is a copper, tin alloy with high elongation and medium hardness. Bronze is characterized by good wear properties, resistance to atmospheric corrosion, and resistance to cavitation in sea water. Typical applications include components and housings for devices in sea water environments.

Chemical Composition (nominal), %

Element / Material	Cu	Sn	Al	Fe	Mn	Ni	P	Pb	S	Sb	Si	Zn
Bronze CuSn10 10-45 μm ¹	Bal.	9.0 - 11.00	0.01	0.2	0.1	2.0	0.2	1.0	0.05	0.2	0.02	0.5

Mechanical Data ⁵	Formula Symbol and Unit	CuSn10 ^{2,3}
Tensile strength	R_m [MPa]	495 \pm 17
Offset yield stress	R_e [MPa]	373 \pm 7
Break strain	A [%]	16 \pm 4
Reduction of area	Z [%]	16 \pm 3
E-Modul	E [GPa]	116 \pm 16
Hardness byVickers	[HV10]	159 \pm 1
Surface roughness	R_a [μm]	10 \pm 2
Surface roughness	R_z [μm]	71 \pm 13

1 Layer thickness 30 μm
2 Layer thickness 50 μm
3 As built

4 Heat treated
5 Process conditions and parameters according to SLM Solutions standards

Material Characteristics

- Good mechanical properties
- Resistance to cavitation in sea water
- Good corrosion resistance
- Good thermal conductivity

Typical Application Areas

- Maritime
- Heat exchangers

Figure 54. Summary of SLM Solutions CuSn10 powder (SLM Solutions, 2018).